Recent achievements on tests of series gyrotrons for W7-X and planned extension at the KIT Gyrotron Test Facility

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Parasitic beam tunnel oscillations have been hampering the series production of gyrotrons for W7-X. This problem has now been overcome thanks to the introduction of a specially corrugated beam tunnel. Two gyrotrons equipped with the new beam tunnel have fully passed the acceptance tests. Despite excellent power capability, the expected efficiency has not yet been achieved, possibly due to the presence of parasitic oscillations suspected to be dynamic after-cavity-oscillations (ACI's) or due to insufficient electron beam quality. Both theoretical and experimental investigations on these topics are ongoing. On previous W7-X gyrotrons collector fatigue has been observed, not (yet) leading to any failures so far. The plastic deformation occurring on the collector has now been eliminated due to the strict use (on all gyrotrons) of a sweeping method which combines the conventional 7 Hz solenoid sweeping technique with a 50 Hz transverse-field sweep system.

Starting in 2013, the gyrotron test facility at KIT will be enhanced, chiefly with a new 10 MW DC modulator, capable of testing gyrotrons up to 4 MW CW output power with multi-stage-depressed collectors.

Keywords: ECRH; gyrotron; beam tunnel; multi-stage depressed collector; parasitic oscillations; FULGOR

1. Remedy of beam tunnel parasitic oscillations in W7-X gyrotrons confirmed

The problems with (backward-wave) parasitic beam tunnel oscillation on several (TH1507) W7-X series production gyrotrons [1], [2] have been overcome with a corrugated beam tunnel design, as shown in Fig.1 and 2.

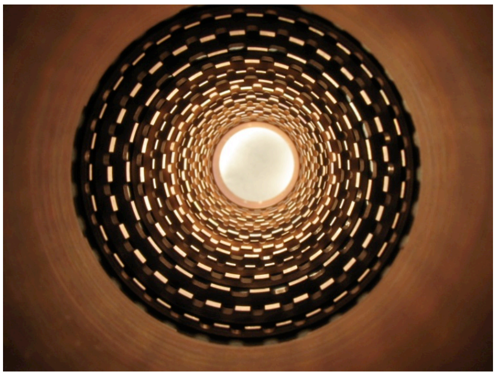

Fig.1 Improved beam tunnel of the W7-X gyrotron

Series production gyrotrons no. SN4R and SN6, both equipped with a corrugated beam tunnel, have successfully passed the factory acceptance tests (FAT) at KIT (180s, 920 kW) and the site acceptance tests (SAT) at W7-X in Greifswald. Actually SN4R is the first TH1507 gyrotron which has surpassed the 1 MW limit during a 6 minute pulse!

Nevertheless, despite excellent power capability, the efficiency shown by these gyrotrons is lower than expected, 37-41% with 27-29 kV of depression voltage, instead of approx. 45% as expected and specified. The reasons for the somewhat poor efficiency are still under investigation. One possible cause might be the presence of a low level parasitic oscillation around 131 GHz, thought to be a dynamic ACI (after cavity interactions [3], [4]). This suspicion is supported by the fact that simulations and observations are in relatively good agreement. This ACI is not disturbing the main mode, but may spread the spent electron beam energy spectrum after the cavity, which in turn may limit the viable depression voltage.

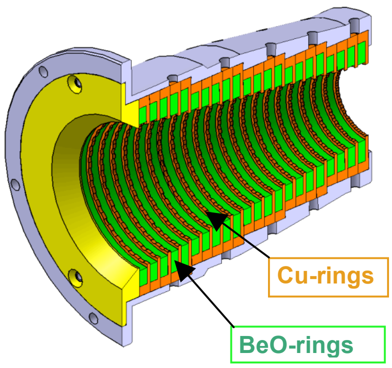

Fig.2 Improved Beam tunnel with corrugated copper rings and a conical contour

Another possible cause for the efficiency limitation which is under theoretical and experimental investigation is the quality of the emitted electron beam in the gun region. A special device (see Fig. 3) is being constructed for measuring the uniformity of the emission current on a cathode. The entire cathode can be rotated, while a row of fine current probes imbedded into a fixed copper anode measure the emitted current along a chord perpendicular to the emitter-ring.

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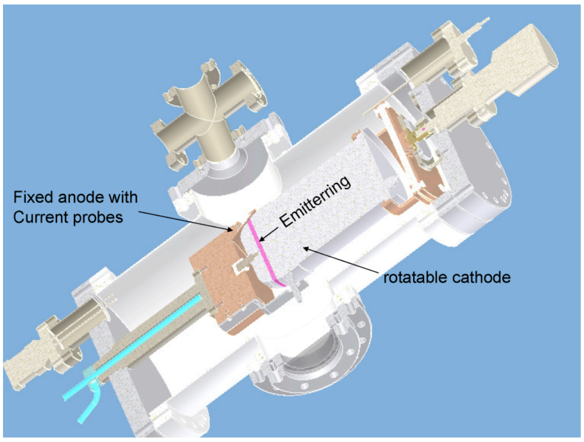

Fig. 3 Electron emission measurement test-setup

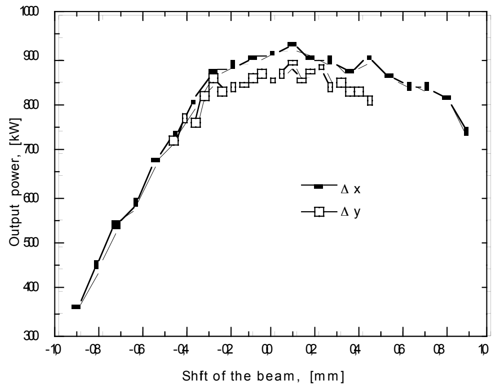

Fig.4 Effect of beam-cavity misalignment on output power

Experimental and theoretical work on the α-spectrum is being carried out also, to find possible causes of the low efficiency of these gyrotrons.

Another point of concern is the alignment of the electron beam with the gyrotrons resonator. From other experiments (with the KIT frequency step tunable gyrotron, operating at 140 GHz) the power dependence as a function of field misalignment (by means of dipole coils, not available on the W7-X magnets) can be seen in Fig. 4. Misalignment beyond 0.3 mm clearly starts to have a strong impact on the obtainable output power.

2. Experimental and theoretical observation of remaining parasitic oscillations

A very powerful frequency measurement system has been developed at KIT [5], employing a STFT (Short-Time Fourier Transform) technique, which records the evolution of the gyrotron frequency spectrum with high temporal and frequency resolution and a high dynamic range of 60 dB's.

The system employs harmonic mixers, but it performs ambiguity checks and automatically recognizes and removes erroneous mixing products. It is capable of providing a frequency spectrum typically every 2 μs, with a frequency resolution of 500 kHz for a duration of (currently) up to 4 ms. The system can be post-triggered, that means it is possible to investigate the spectral evolution around the time of a pulse failure in order to gain deeper insight into the processes leading up to such a pulse disruption.

Current system parameters	
RF input range	110-170 GHz (D-Band)
Maximum acquisition time	4 ms
Real-time bandwidth	6 GHz
Dynamic range	60 dB
Frequency resolution	0.1-10 MHz (typ.)

Table 1: Capabilities of f-spectrum measurement system

Figure 5 gives a block diagram of the system, which employs two identical measurement chains with slightly offset local oscillators, which are necessary to perform the mentioned automatic mixing-ambiguity checks.

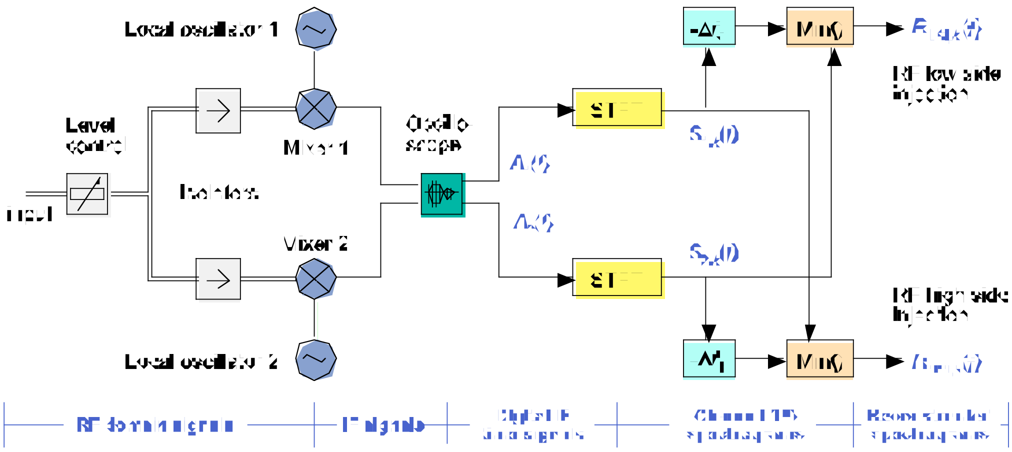

Fig.5 KIT gyrotron spectral measurement system

Figure 6 shows a so called "waterfall" diagram of the W7-X SN6 tube when operated at high power (900 kW) and high current (> 44 A). A parasitic mode, suspected to be a dynamic ACI, exhibits discrete frequency jumps and low frequency modulation. Efforts are also being made [6] to enhance the existing interaction-code (SELFT), in order to predict, explain and hopefully avoid ACI's in future gyrotron designs. As can be seen in Fig.7, the initial results obtained with the modified code are in good agreement with experimental observations (Fig.6). These parasitic modes co-exist together with the 140 GHz main mode without noticeable disturbance.

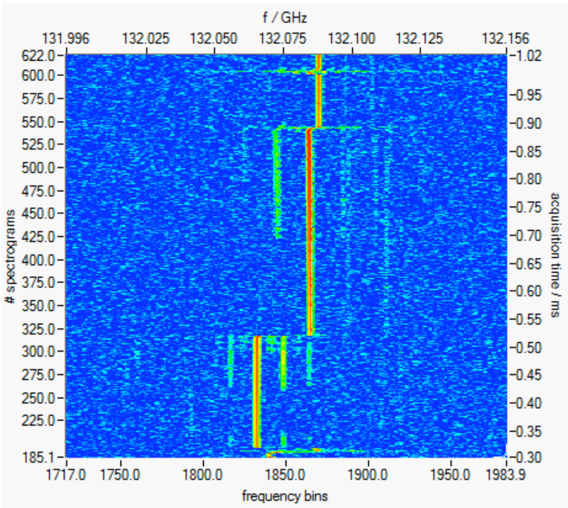

Fig.6 Waterfall diagram of 132 GHz parasitic mode during a high power pulse with a W7-X series-production gyrotron. The dynamic range of these signals is ≈ 60 dB!

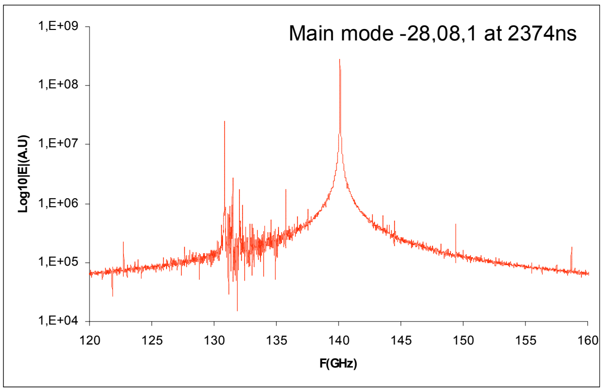

Fig.7: Mono-mode simulation (power density spectrum, considering $dB/dz \neq 0$), predicting the presence of parasitic modes (ACI's in the up-taper region) in agreement with experimental observations

3. Other technological improvements on the W7-X gyrotrons

The spent electron beam on the W7-X collector is swept up- and down with 7 Hz by a conventional vertical field sweeping system (VFSS), thus reducing the power deposition to less than 500 W/cm^2. The collectors of these gyrotrons have never failed yet, but there has always been evidence of plastic deformation at the reversal points, where the collectors have shown noticeable denting (3-5mm). By using the 7 Hz VFSS system along with a 50 Hz transverse field sweep system (TFSS, see [7]), the thermal loading has now been reduced to a level, where no such denting can be observed any more. Figure 8 shows a comparison of the temperature excursion between the solenoid and the combined sweep systems (recorded by thermocouples embedded in the collector). In future all W7-X gyrotrons will be equipped with this combined sweeping system.

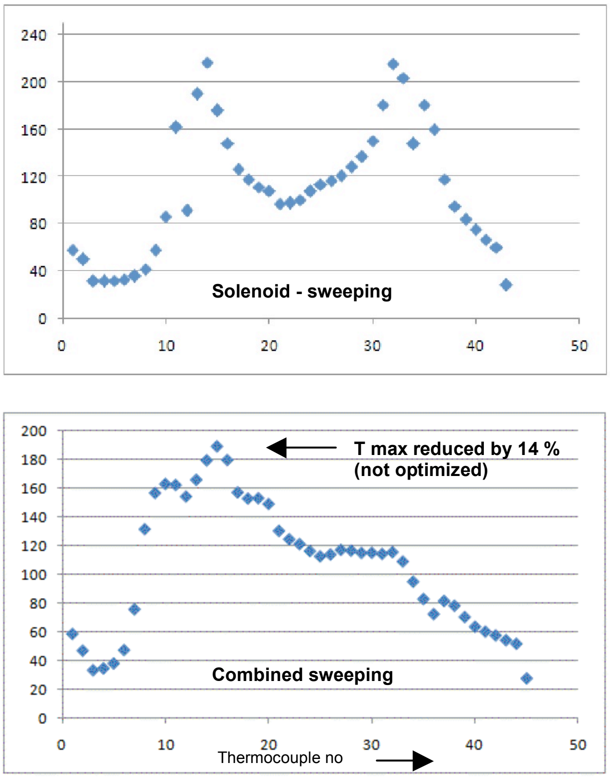

Fig.8 Collector temperature (at KIT) for TH1507 SN6 tube with 1.5 MW dissipation for the two sweeping methods

At W7-X a reduction of T_{max} by as much as 40% has been achieved. It should be noted, that the temperature excursion on the inside of the collector is reduced 2.7 times more than recorded by the thermocouples, due to the much higher sweeping frequency of 50 Hz, thus reducing the thermal fatigue considerably. No more plastic deformation has been observed on gyrotrons exclusively operated in this way.

4. FULGOR (Fusion Long Pulse Gyrotron Laboratory), the new gyrotron test facility at KIT

In 2013 KIT is starting to upgrade the existing gyrotron test facility. The new facility, named **FULGOR**, shall be able to test CW gyrotrons with up to 4 MW Output power (2 output beams) with a **multistage depressed**

collector (MSDC). The main investment will be a 10 MW solid state DC modulator, capable of pulses up to 130 kV at 120 A in short-pulse-mode (also known as non-depressed mode), and pulses of 90 kV and 120 A in CW-mode. CW in this instance meaning pulses of up to 3600s with a maximum duty cycle of 50%. The two configurations can be seen in Fig. 8a and 8b respectively.

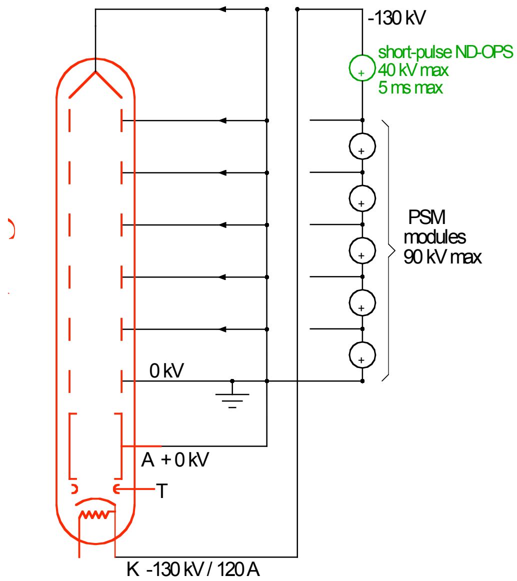

Fig.8-a MSDC gyrotron in non-depressed short-pulse operation. All collector segments are at ground potential.

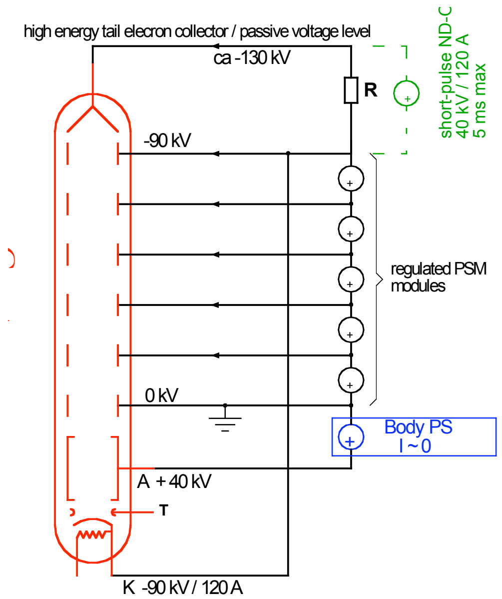

Fig.8-b MSDC gyrotron in CW operation. The tap voltage for the intermediate collector segments needs to be kept constant despite current fluctuations.

While high power MSDC-gyrotrons are not currently state-of-the-art, the need to enhance the efficiency of gyrotrons for future ECRH systems for reactors such as DEMO, will necessitate the development of MDSC gyrotrons. These may feature up to 10 collector segments of different voltage potential. Table 1 lists the tentative specification for this modulator.

Polarity	Negative output voltage , floating to 1.5 kV
Output voltage for short pulse (5ms) operation:	0 kV to 130 kV
Output Voltage for CW Operation:	0 kV to 90 kV
Maximum output voltage ripple:	< 300 V_{p-p} any load, any frequency
Max. rise time (10%-90%)	50 µs
Max. overshoot / settling time	0.1% / 100 µs (1%undershoot acceptable)
3-phase mains supply voltage	20 kV (+2% / -6%)
Maximum inrush current at 20 kV grid	< 500 A_{rms} each phase
Apparent power from 20 kV mains grid	max. 12.5 MVA, (≥ 12 pulse)
Modulation capability up to 1 kHz and 5 kHz	30kV /20 kV
Max. energy deposition into an arc	10 Ws (arc voltage ≈ 100V)
Adjustable over-voltage protection	10-130 kV (switch-off in less than 10µs)
Adjustable over-current protection	5-120 A (switch-off in less than 10µs)
Stability of intermediate voltage taps (selectable at random in 1-2 kV steps)	+/- 500 V (1 kV_{p-p})

Table 1: Abridged specification for the FULGOR 10 MW gyrotron cathode voltage modulator

5. Summary

Series production of W7-X gyrotrons has resumed after solving the problem with beam tunnel oscillations. Collector lifetime concerns have been alleviated with an enhanced sweeping system. Investigations into causes of the limited efficiency on some tubes are ongoing. The upgrade of the KIT gyrotron test facility due to start next year with the procurement of a CW 10 MW modulator has been presented.

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