High Power Gyrotron Development for Advanced Fusion Devices

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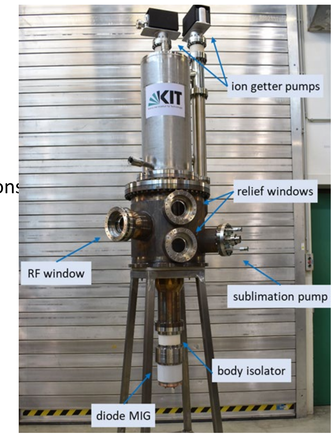
1. Introduction

- Gyrotron oscillators are a major development at KIT for Electron Cyclotron Resonance Heating (ECRH) and non-inductive Current Drive (CD)
- Coaxial and conventional hollow cavity gyrotron technology, hollow cavity: 1 MW-class gyrotrons, coaxial cavity gyrotron:higher output power and higher operating frequency
- Development and manufacturing of a 1.5 MW, 140 GHz short pulse pre-prototype gyrotron for W7-X
- Progress with a modular, short pulse 2 MW, 170 GHz coaxial cavity gyrotron towards longer pulse operation
- R&D of a multi-frequency design of the coaxial cavity gyrotron, 170 GHz, 204 GHz and 238 GHz operation. Experiments will be performed in the new KIT gyrotron teststand FULGOR which includes a new 10.5 T superconducting magnet.

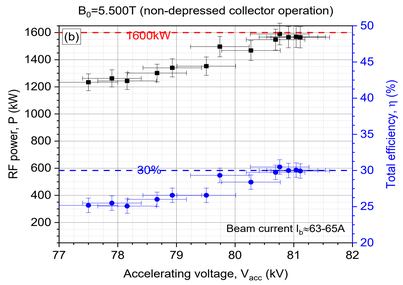
2. 1.5 MW, 140 GHz gyrotron for W7-X – design and first results of a short pulse prototype

- W7-X: increase the gyrotron unit power from 1 MW to 1.5 MW at 140 GHz in CW operation
- 1.5 MW design based on the existing 1 MW, 140 GHz gyrotron
- Short pulse pre-prototype gyrotron for verification of the physics design of the gyrotron
- Industrial CW gyrotron to be built at THALES, Velizy, France
- Design concept:
  - Redesign of MIG using in-house coded ARIADNE [1] and ESRAY [2] to ensure high electron beam quality at 55 – 60 A
  - Beam Tunnel: stacked concept with alternating ceramics and copper rings with corrugations
  - Cavity: 1.5 MW output power in the $TE_{28,10}$ mode at 140 GHz, cavity radius= 22.83 mm, Ohmic wall losses <~2.2 kW/cm^2, RF design of the cavity validated by multi-mode simulations with EURIDICE [4]
  - Mirror-line launcher and three mirrors with quadratic surface contour function: conversion of $TE_{28,10}$ mode to TEM_{00} 99% @ window (TWLDO [5])

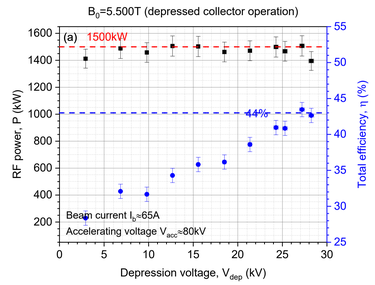


Operating cavity mode	$TE_{28,10}$
Frequency	140 GHz
Electron beam current	55 A
Accelerating voltage	80 kV
Velocity ratio (pitch factor)	~ 1.2
Cavity magnetic field	5.56 T
Efficiency with SDC	> 46 %
Electron beam radius in cavity	10.1 mm
RF power at end of uptaper	1.83 MW
Ohmic losses	61 kW
Max. Ohmic cavity wall loading	2.2 kW/cm^2

Gyrotron design parameters and performance results.



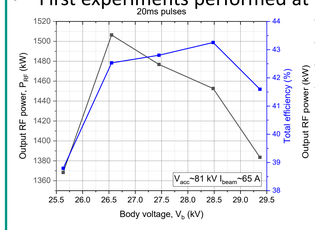
RF power and efficiency versus accelerating voltage, pulse length = 0.5 ms.



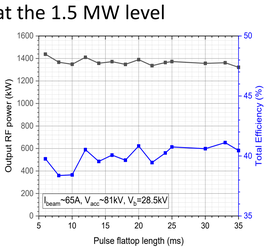
RF power and efficiency versus depression voltage, pulse length = 1 ms.

3. 2 MW, 170 GHz coaxial cavity gyrotron for 100 ms operation

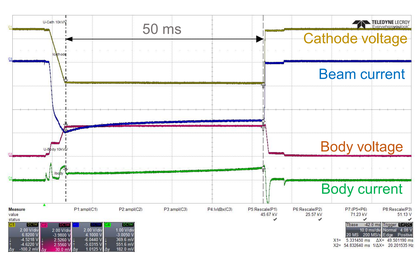
- Development goal: modular pre-industrial 2 MW, 170 GHz gyrotron, pulse length up to several 100 ms
- Development is based on the existing 2 MW, 170 GHz coaxial cavity gyrotron operating in the $TE_{34,19}$ mode [6].
- Upgrade of basic configuration:
  - active water cooling systems for the beam tunnel, cavity, mirror box and collector
  - Baking procedure in a N_2 furnace at T= 350 °C (pressure level ~10^{-10} mbar).
- First experiments performed at the 1.5 MW level



Output power and total efficiency (in depressed collector operation) versus body voltage V_b (depression voltage), pulse length 20 ms,



Constant output power for different pulse lengths achieved

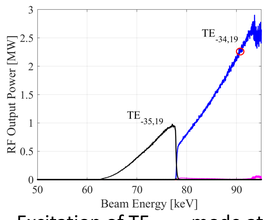


4. 170/204 GHz 2 MW Development for DEMO

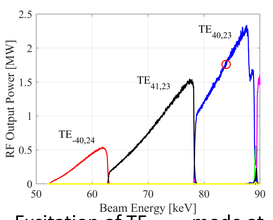
- Starting point: $TE_{34,19}$ mode 2 MW 170 GHz gyrotron
- To be tested with the 10.5 T SC magnet of FULGOR (170/204/238 GHz)
- First experiments (short pulse) with existing coaxial diode Magnetron Injection Gun
- 170 GHz: $TE_{-34,19}$ mode (counter rotating) at B~ 6.88 T,
- 204 GHz: $TE_{+40,23}$ mode (co-rotating) at B~ 8.23 T
- Low-power test set-up manufactured and $TE_{+40,23}$ mode generated at 203.95 GHz

	$TE_{-34,19}$-mode	$TE_{\pm40,23}$-mode	
	OP1	OP1	OP2
Electron kinetic energy [keV]	90.8	84.0	86.8
Beam current [A]	72	70	67
Magnetic field [T]	6.88	8.21	8.25
Electron velocity ratio	1.2	1.06	1.15
Electron beam radius [mm]	10.58	9.77	9.77
Transverse velocity spread [%]	2.8	2.7	2.57
Kinetic energy spread [%]	0.15	0.10	0.10
RF power at end of up-taper [MW]	2.27	1.79	1.67
Interaction efficiency [%]	35.8	31.5	30.0
Maximum wall loading [kW/cm^2]	2.00	2.00	2.00
Maximum insert loading [kW/cm^2]	0.11	0.06	0.06
Frequency [GHz]	170.0	204.13	204.13

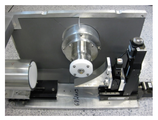
Simulated nominal operating points for the 170/204 GHz gyrotron

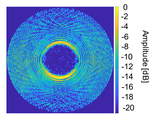


Excitation of $TE_{-34,19}$ mode at 170 GHz and operating point



Excitation of $TE_{+40,23}$ mode at 204 GHz and operating point





Low power mode generator (left) and measured E-field distribution of the$TE_{+40,23}$ mode at 204 GHz (right) taken with a fundamental rectangular waveguide probe for vertical polarisation

5. Conclusions

- A conventional **1.5 MW gyrotron** has been designed, a short pulse version has been manufactured. First results of the short pulse gyrotron show excellent agreement with the simulations.
- First tests with **increased pulse length of the existing modular 170 GHz, 2 MW coaxial-cavity gyrotron** show a successful pulse length extension up to 50 ms. Experiments showed that additional measures must be taken to improve the vacuum condition in long pulses.
- A dual frequency gyrotron at 170/204 GHz has been designed using existing components. A careful mode selection has been performed in order to ensure proper operation for both frequencies. Low-power measurements of the quasi-optical mode converter show excellent results.

References

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