Considerations for the dual-frequency operation of 140 GHz Megawatt-class W7-X gyrotrons at 175 GHz for CTS plasma diagnostics

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- Motivation
- Structure of the W7-X Gyrotron
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- Conclusion & Outlook

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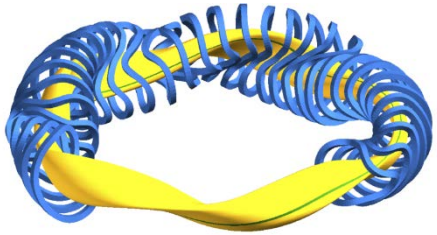
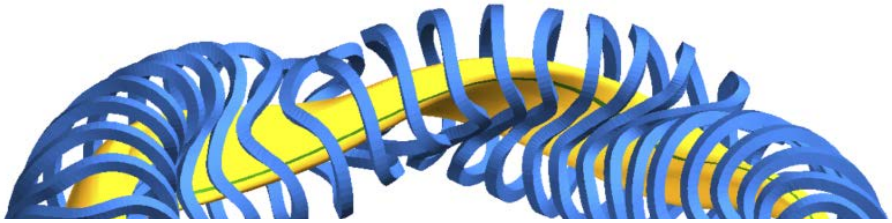
Wendelstein 7-X (W7-X)

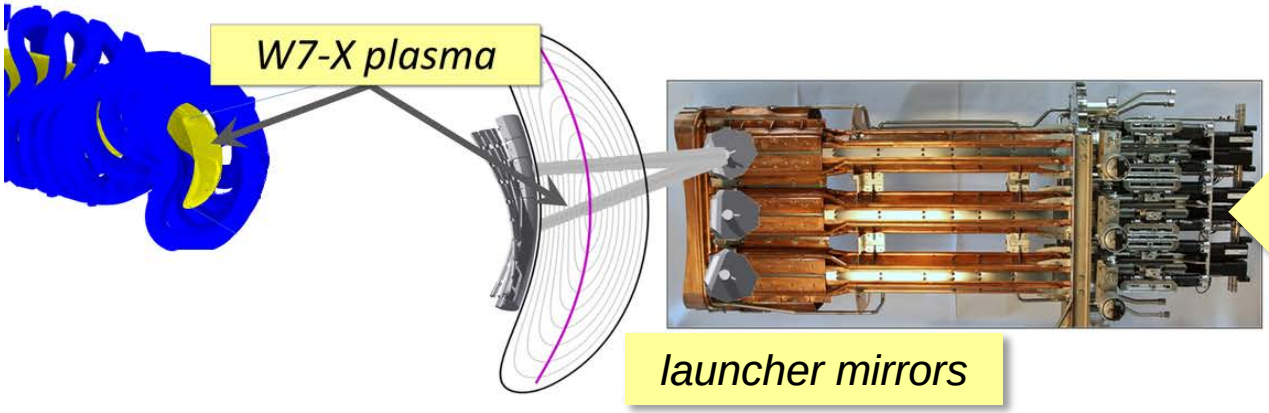


- Stellarator W7-X is an experimental reactor to demonstrate fusion relevant plasma performance
- **Heating** of the plasma through Electron Cyclotron Resonance Heating

  ➡ 10 **gyrotr**



- Gyrotrons oper ·on **resonance**

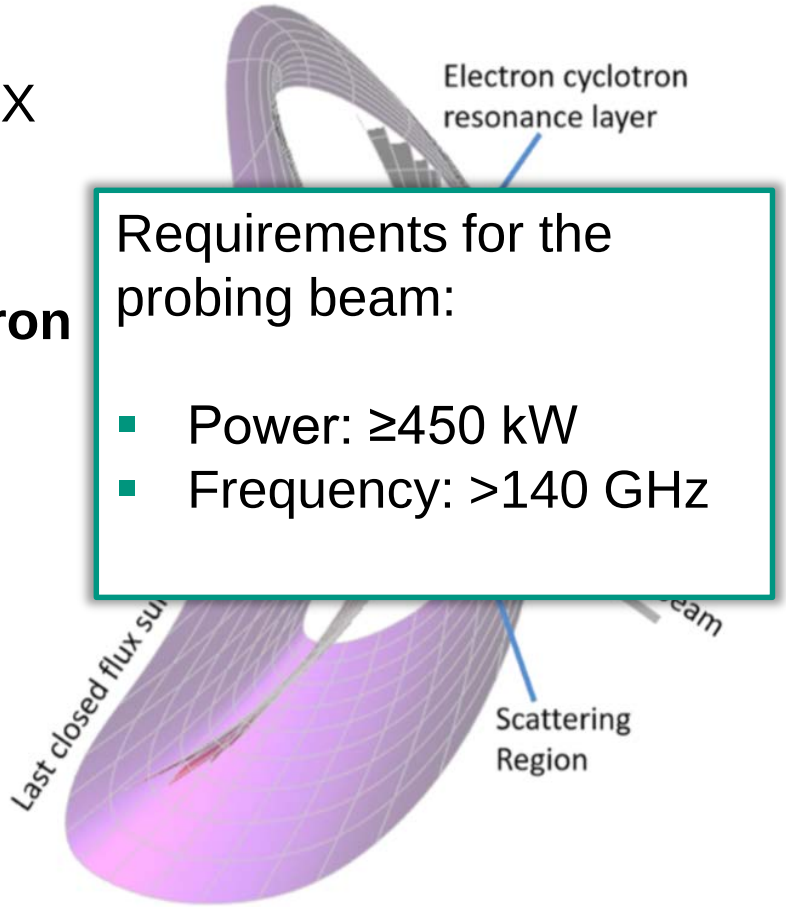


Quasi-optical transmission

Gyrotron

Collective Thomson Scattering (CTS)

- CTS diagnostic of the plasma:
  Measurement of ion temperature at W7-X
- Probing beam needs high power
  Source at W7-X: **140 GHz ECRH gyrotron**
- **Absorption** of **140 GHz** wave
  ➡ measurement in electron cyclotron resonance layer not possible
- Refractions in plasma at lower frequencies
  ➡ **higher frequency** for CTS at W7-X needed



Requirements for the probing beam:

- Power: ≥450 kW
- Frequency: >140 GHz

Motivation

Is it possible to operate the **existing 140 GHz gyrotron** at a **higher frequency**?

- Operation of a gyrotron at a different frequency is not straightforward

  ➡ W7-X gyrotron was designed and optimized specifically for 140 GHz

- Operation at a different frequency requires **investigation of the subcomponents** of the gyrotron

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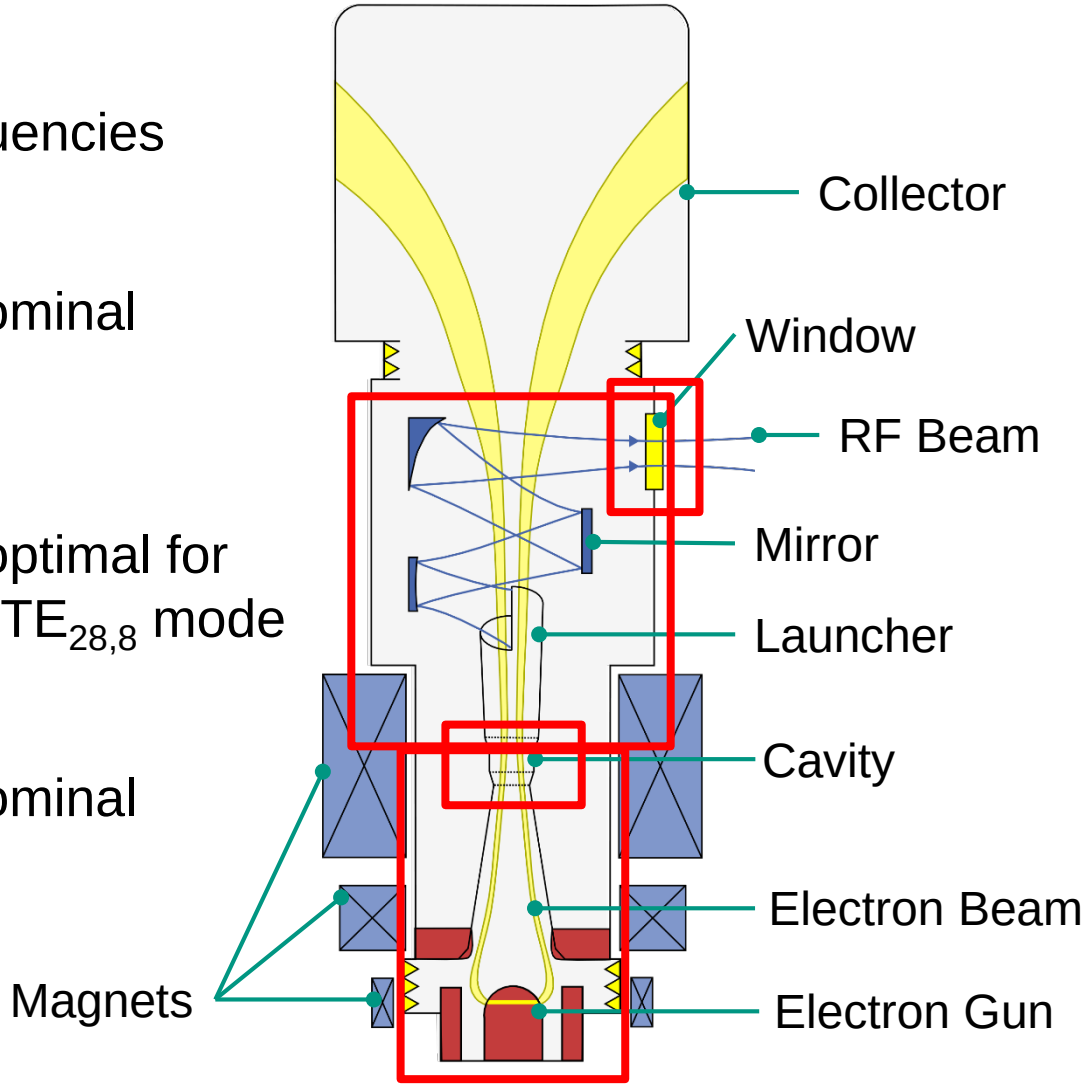
Structure of the 140 GHz W7-X Gyrotron

- Window transparency
  - ➡ limits possible frequencies
- Quasi-optical system
  - ➡ optimized for the nominal $TE_{28,8}$ mode
- Electron gun
  - ➡ Beam parameters optimal for interaction with the $TE_{28,8}$ mode
- Cavity
  - ➡ optimized for the nominal $TE_{28,8}$ mode



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Window Transmission

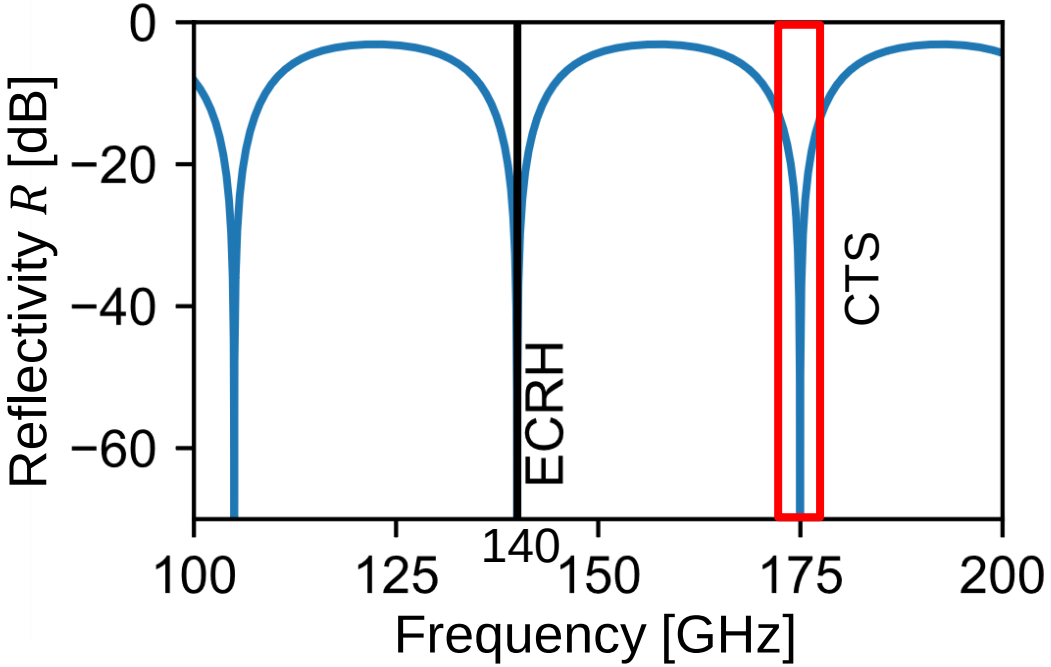
- Diamond window is transparent if window thickness d_w is a multiple of half of the wavelength inside the window:

$$d_w = m\,\frac{\lambda}{2} \quad \Leftrightarrow \quad f = m\,\frac{c_0}{2\sqrt{\varepsilon_r}\,d_w}$$

with $m = 1,2,\ldots$; d_w = 1.8 mm;

ε_r = 5.67

- Closest higher frequency compatible with the window thickness: **175 GHz**



m	f [GHz]
3	105
4	140
5	175

Frequency range for R < 2.5 %:
173.2 GHz - 176.8 GHz

Identification of Possible TE Modes

- Nominal mode for operation at 140 GHz: $TE_{28,8}$
  - ➡ Operation at 175 GHz requires different TE mode

- Criteria for a suitable TE mode:

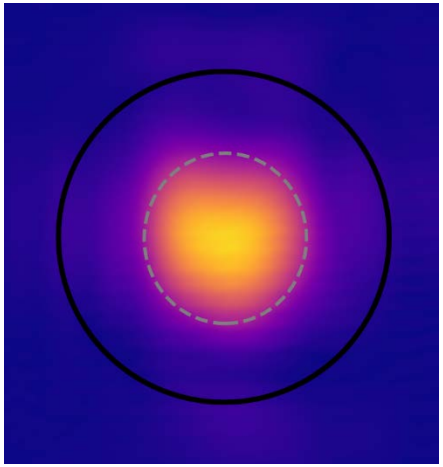
Cut-off frequency f_c: Excitation of the mode near cut-off frequency
  - ➡ Should be close to 175 GHz for low reflections at the window

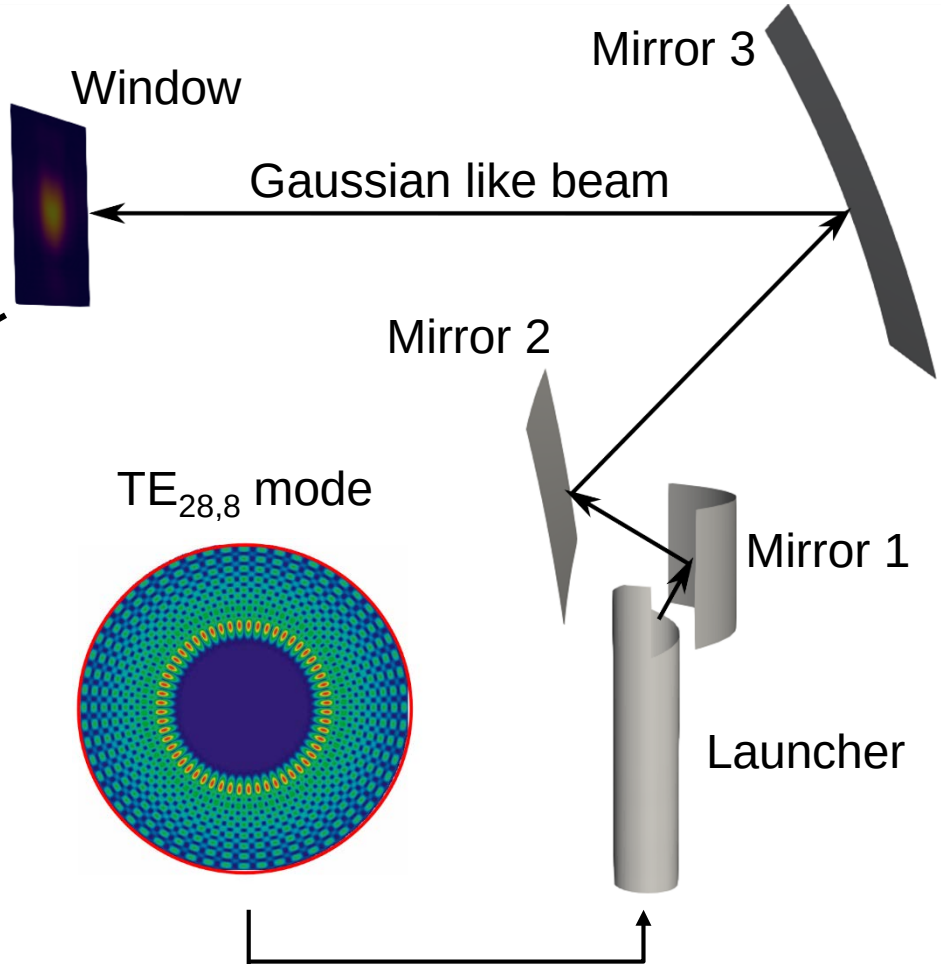
Caustic radius r_c: Determines conversion into Gaussian beam
  - ➡ Should be close to the one of the nominal $TE_{28,8}$

Mode	f_c [GHz]	R [%]	r_c [mm]
$TE_{28,8}$	140.02	0.002	10.2
$TE_{29,12}$	175.26	0.07	8.44
$TE_{32,11}$	176.08	0.96	9.27
$TE_{34,10}$	173.72	1.18	9.99
$TE_{35,10}$	176.59	2.00	10.11

Launcher and Mirror System

- Launcher converts the cylindrical TE mode into a Gaussian like beam
- Simulation results for the $TE_{28,8}$ mode at the window: Gaussian mode content (G.M.C.) at the window: 97%

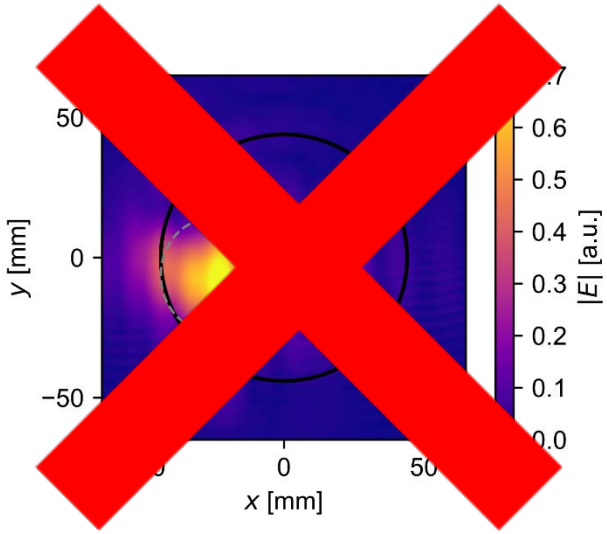




Candidate Modes at the Window

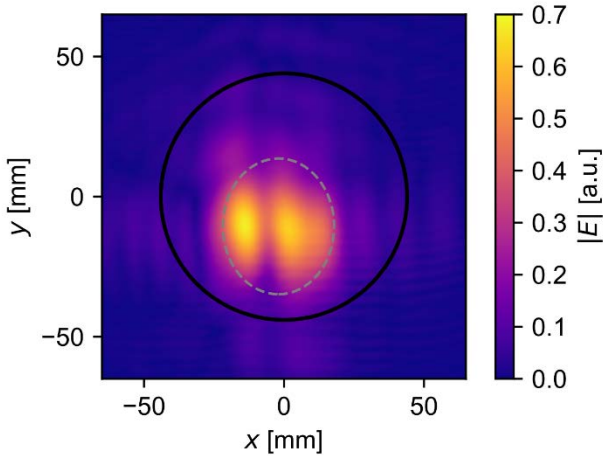
$TE_{29,12}$

f_c = 175.2 GHz
r_c = 8.44 mm
G.M.C. = 70.9%
R = 0.07%



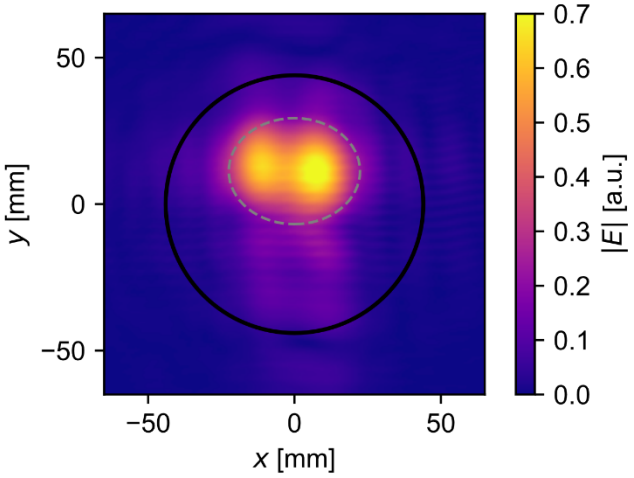
$TE_{32,11}$

f_c = 176.1 GHz
r_c = 9.27 mm
G.M.C. = 76.3%
R = 0.96%



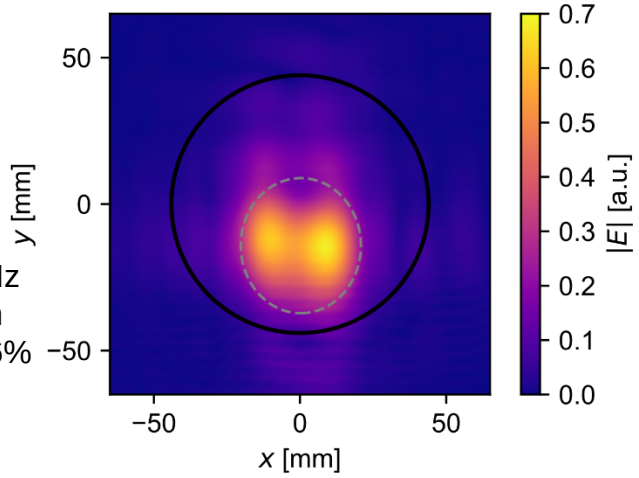
$TE_{34,10}$

f_c = 173.7 GHz
r_c = 9.99 mm
G.M.C. = 87%
R = 1.18%



$TE_{35,10}$

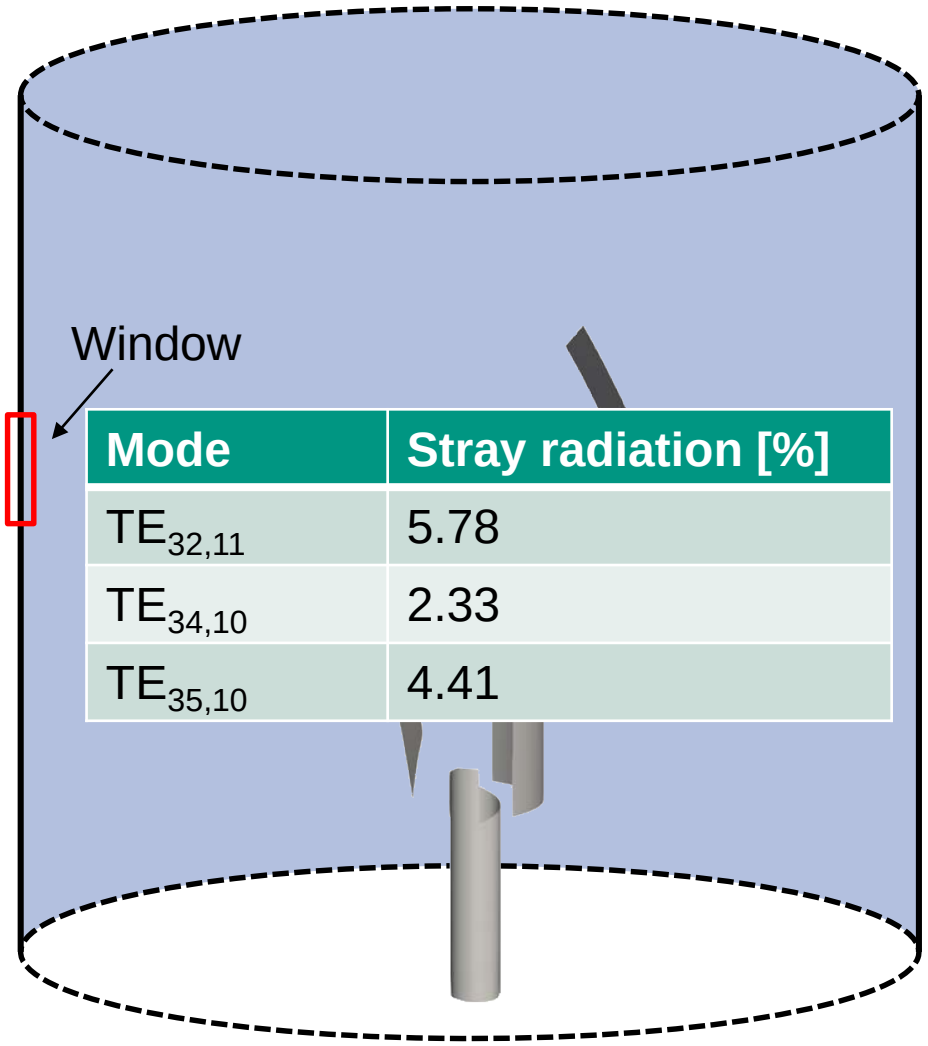
f_c = 176.5 GHz
r_c = 10.11 mm
G.M.C. = 87.6%
R = 2.00%



Stray Radiation inside the Gyrotron

- Cylinder around the quasi-optical system
  - Radius: 300 mm
  - Length: 1200 mm
- Calculation of total power on the cylinder surface P_{tot}
- Calculation of power exiting the window P_{window}
- Stray radiation:

$$\frac{P_{\mathrm{tot}} - P_{\mathrm{window}}}{P_{\mathrm{tot}}}$$



Mode	Stray radiation [%]
$TE_{32,11}$	5.78
$TE_{34,10}$	2.33
$TE_{35,10}$	4.41

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Electron Gun Operation

- Geometry of W7-X electron gun is fixed

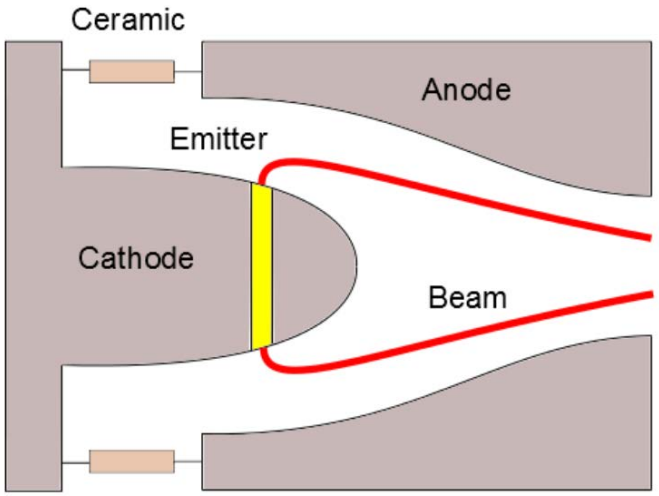
- Parameters which can be changed:

  Beam voltage V_b

  Beam current I_b

  Magnetic field B_c

- Definition of operating points (OPs)
  - ➡ calculation of V_b and I_b depending on B_c based on simplified calculations to get an output power of 500 kW



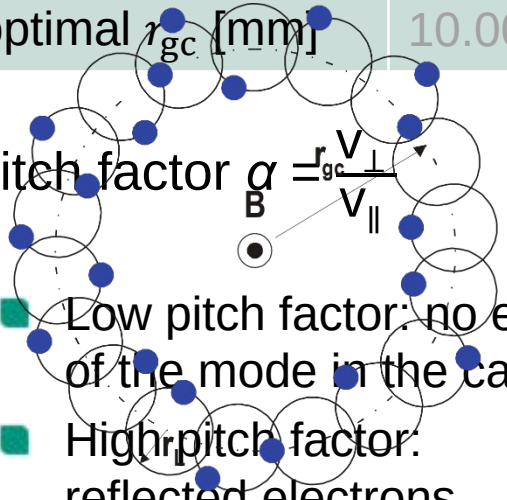
OP	B_c [T]	V_b [kV]	I_b [A]
OP1	6.6	45	53
OP2	6.7	54	45
OP3	6.8	62	39
OP4	6.9	71	34
OP5	7.0	79	31

Electron Beam Parameters

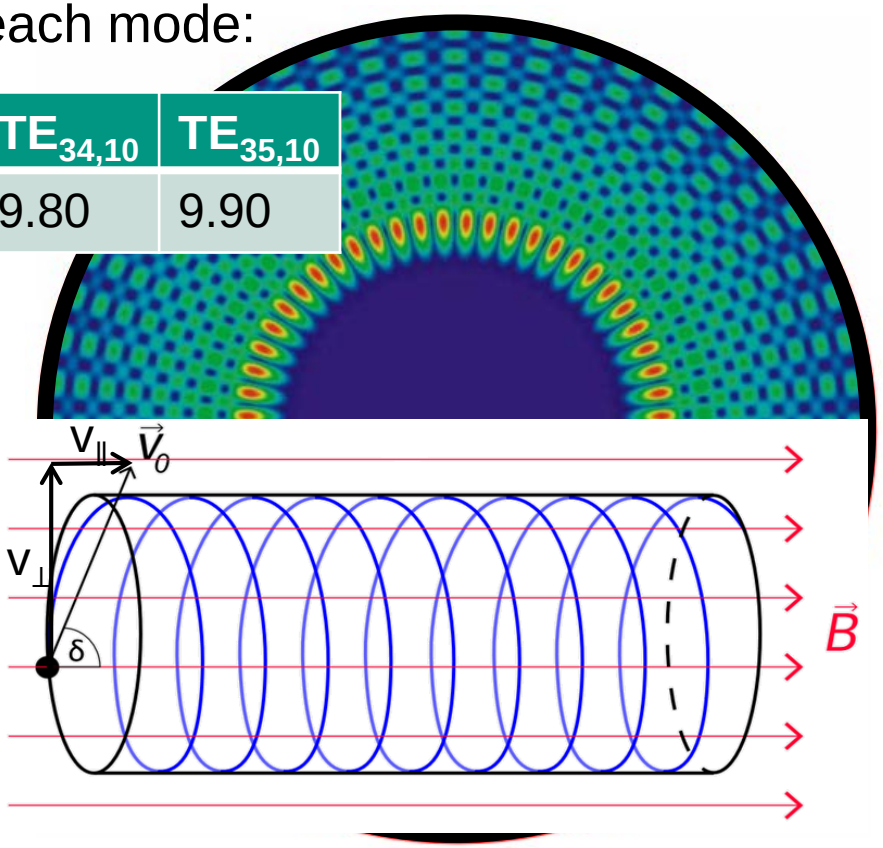
- Electron gun forms a hollow cylindrical electron beam
- Optimal guiding center radius for each mode:

mode	$TE_{28,8}$	$TE_{32,11}$	$TE_{34,10}$	$TE_{35,10}$
optimal r_{gc} [mm]	10.00	9.08	9.80	9.90

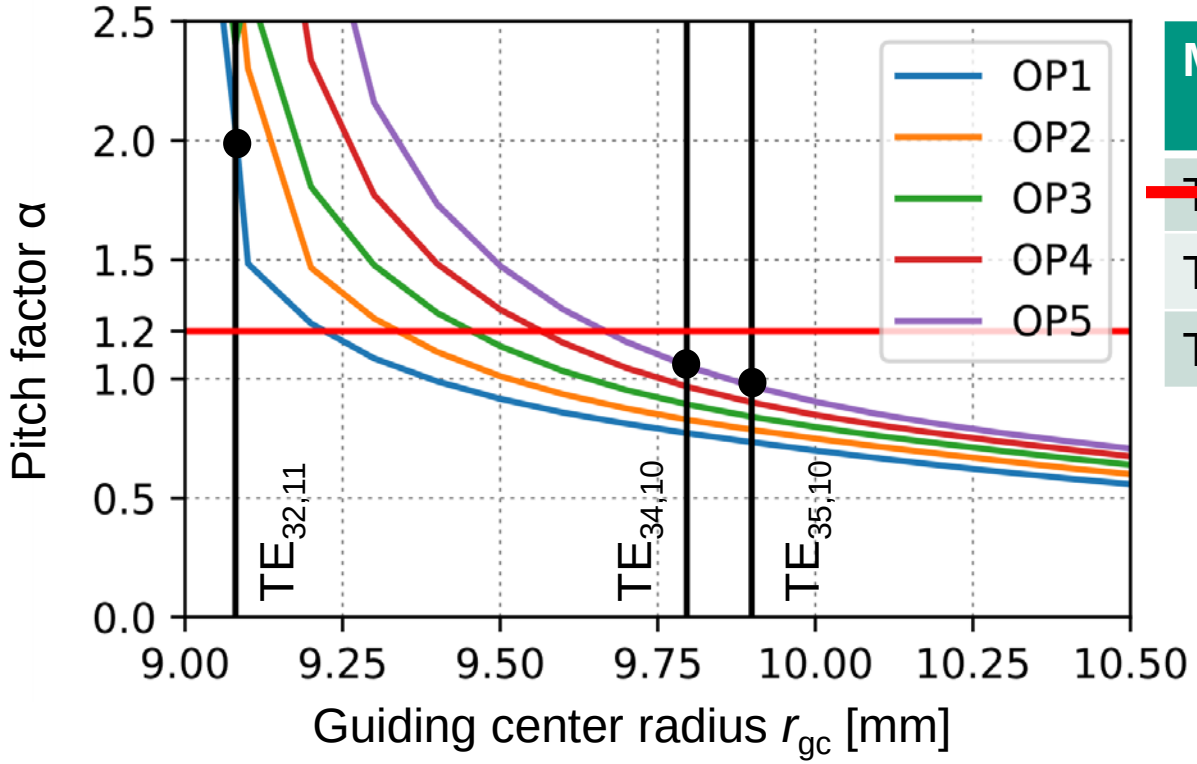
- Pitch factor $\alpha = \frac{v_\perp}{v_\parallel}$
  - Low pitch factor: no excitation of the mode in the cavity
  - High pitch factor: reflected electrons
  - Typical values: 1.2 – 1.4



$TE_{28,8}$ mode



Simulation of the Electron Gun



Mode	Operating Point	α
~~$TE_{32,11}$~~	~~OP1~~	~~**2.00**~~
$TE_{34,10}$	OP5	**1.05**
$TE_{35,10}$	OP5	**0.97**

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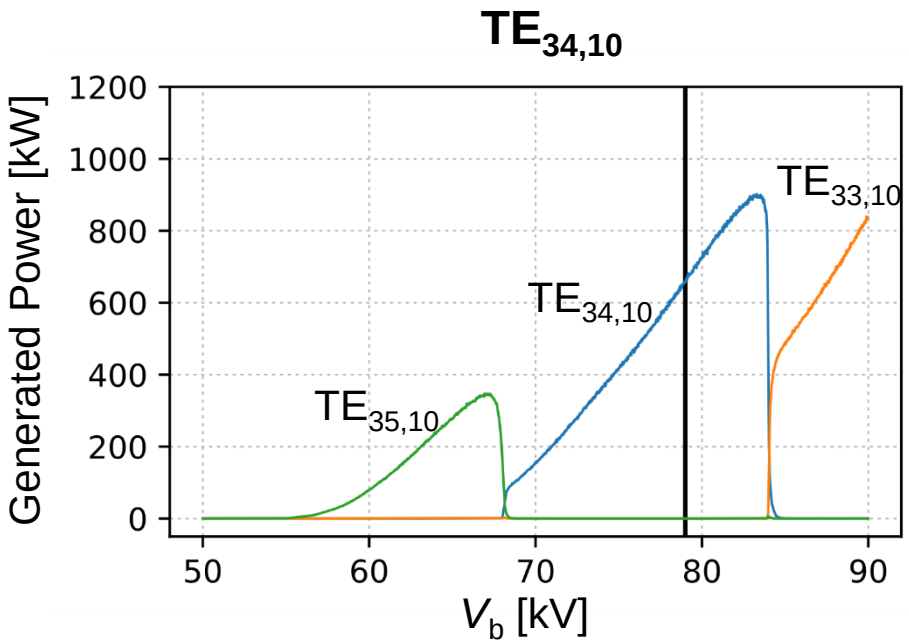
Excitation in the Cavity (1/2)

- Multi-mode analysis for mode competition
  - Competitor modes could disturb excitation of desired mode
  - 40 potential competitor modes were analyzed

- Generated power in dependence of beam voltage:



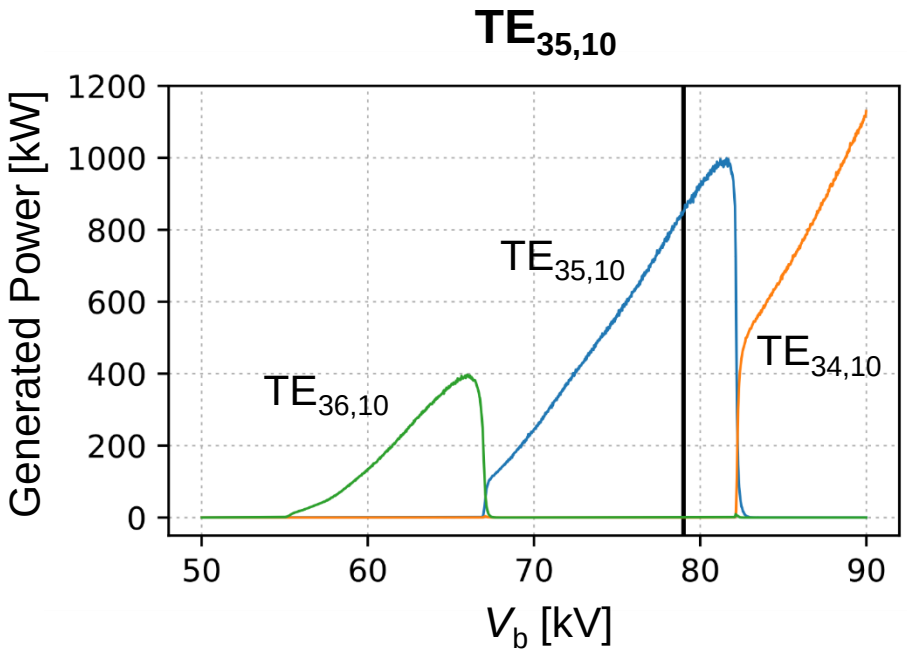
Operating Parameters:
B_c = 6.98 T
I_b = 40 A
V_b = 79 kV

Generated Power at nominal V_b: 660 kW

Excitation in the Cavity (2/2)

- Multi-mode analysis for mode competition
  - Competitor modes could disturb excitation of desired mode
  - 40 potential competitor modes were analyzed

- Generated power in dependence of beam voltage:



Operating Parameters:
B_c = 7.10 T
I_b = 50 A
V_b = 79 kV

Generated Power at nominal V_b: 850 kW

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Conclusion

- Simulations show that it is possible to operate the W7-X gyrotron at 175 GHz for CTS

Mode	$TE_{34,10}$	$TE_{35,10}$
Excited frequency [GHz]	173.9	176.7
Window reflection [%]	**0.8**	**2.5**
Stray radiation [%]	**2.33**	**4.41**
Gaussian mode content [%]	87.0	87.6
Output power [kW]	660	850
Efficiency [%]	22	22
Beam voltage [kV]	79	79
Beam current [A]	40	50
Magnetic field at the cavity [T]	6.98	7.10

Outlook

- Procurement of a new magnet
  - Operation at 175 GHz requires 7 T at the cavity
  - Current magnet used for the 140 GHz operation can not deliver 7 T

- New Magnet should allow operation at 140 GHz and 175 GHz
  - Discussions with different magnet suppliers are ongoing
  - Magnetic profile for the 140 GHz operation of the new magnet needs to be identical to the magnetic profile of the old magnet
  - In previous simulations, for the 175 GHz operation, the magnetic profile of the 140 GHz operation (upscaled to 7 T) was used
  - Difficulties for the magnet suppliers to deliver a magnet with the requested profiles for the 140 GHz and 175 GHz operation → variations in the magnetic profile for the 175 GHz operation

➡ New simulations for the 175 GHz operation with the magnetic profile provided by the magnet suppliers

Thank you very much for your attention