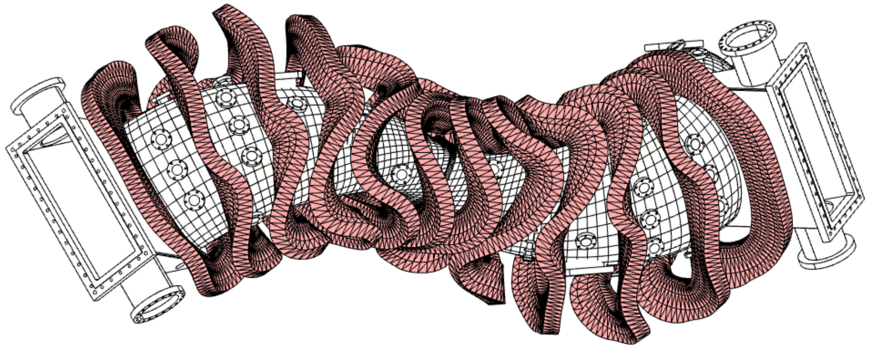
Helically Symmetric eXperiment

Design and Performance of a future 70 GHz ECRH system on HSX

B. Geiger, A. Thornton and the HSX team



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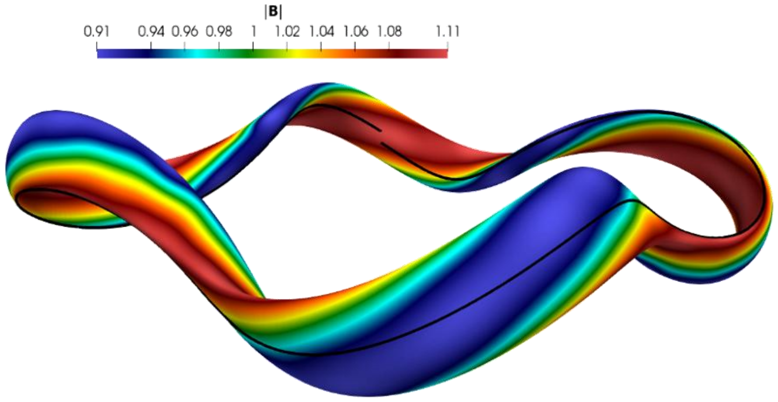
This work was funded the Department of Energy (DoE) under grant number DE-FG02-93ER54222

Outline

- Motivation for a new gyrotron at HSX
- 70 GHz gyrotron
- Power supply
- Transmission line
- Absorption modeling
- Conclusion & outlook



Current 28 GHz system

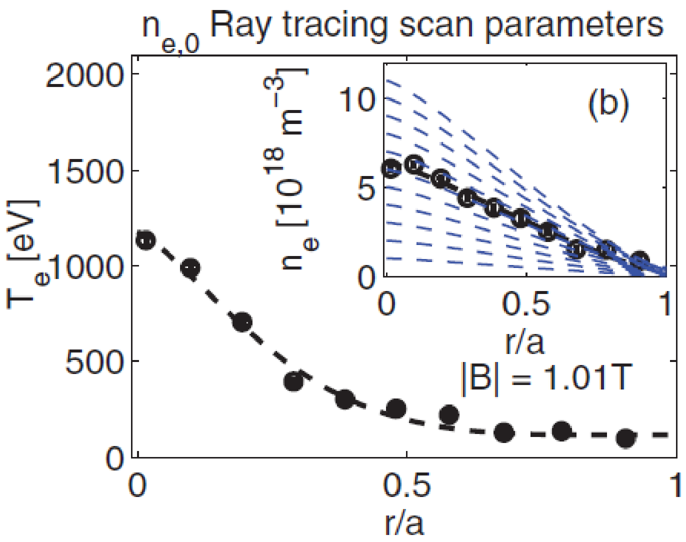
- Resonance at 1 T (O1-mode)
- Cut-off at ~0.97 x 10^{19} m^{-3}
- 30% single pass absorption efficiency

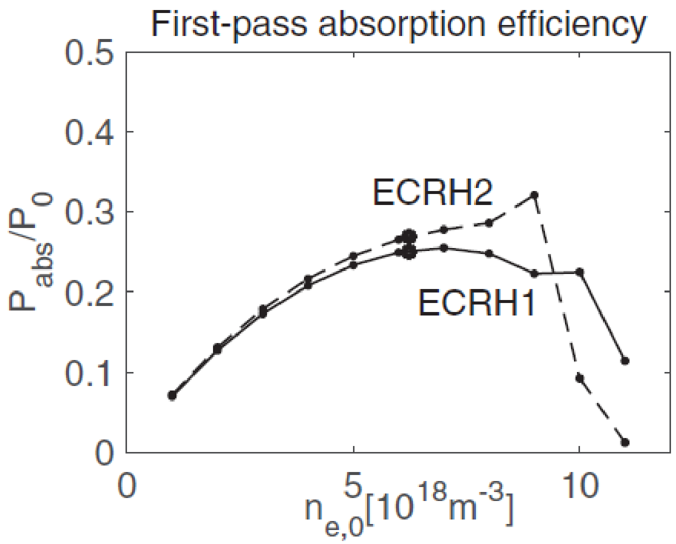
Cut-off densities for the k^{th} harmonic:

$$n_{cut-off}^{O-mode} = 9.65 \times 10^{18} k^2 B^2$$
$$n_{cut-off}^{X-mode} = 9.65 \times 10^{18} k(k-1) B^2$$

B=1T O1-mode → ~9.7 x10^{18} /m^3

H. Zohm et al, FUSION SCIENCE AND TECHNOLOGY VOL. 52 AUG. 2007





G.M. Weir, Nucl. Fusion 55 (2015)

70 GHz ECRH would allow for higher density operation

70 GHz ECRH would provide access to higher density plasmas by:

- Increased magnetic field (1.25 T)
- Second harmonic (k=2)

Higher density yields:

- Higher ECRH absorption efficiency
- Improved electron ion- coupling
- Lower penetration depth of neutrals

Cut-off densities for the k^{th} harmonic:

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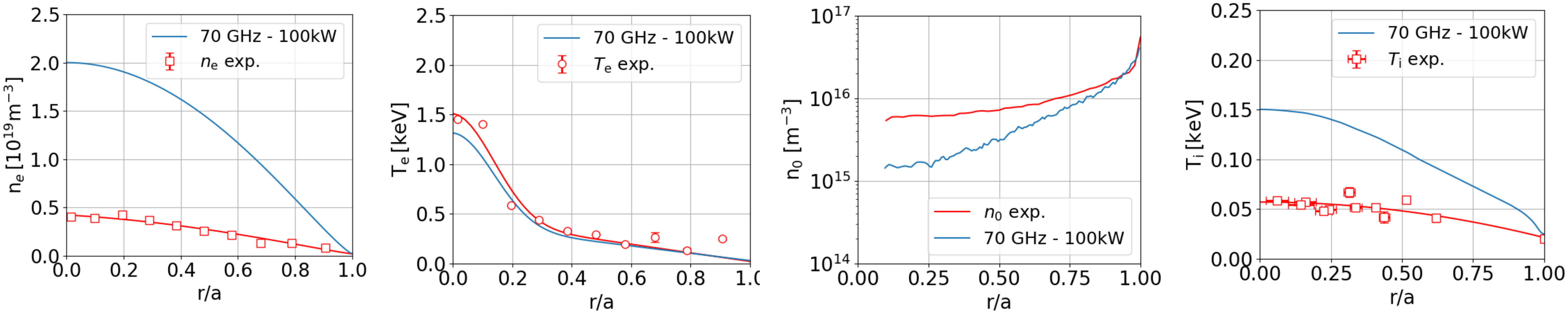
$$n_{cut-off}^{X-mode} = 9.65 \times 10^{18} k(k-1) B^2$$

B=1T O1-mode → ~9.7 x10^{18} /m^3

B=1.25T X2-mode → ~3.0 x10^{19} /m^3

H. Zohm et al, FUSION SCIENCE AND TECHNOLOGY VOL. 52 AUG. 2007

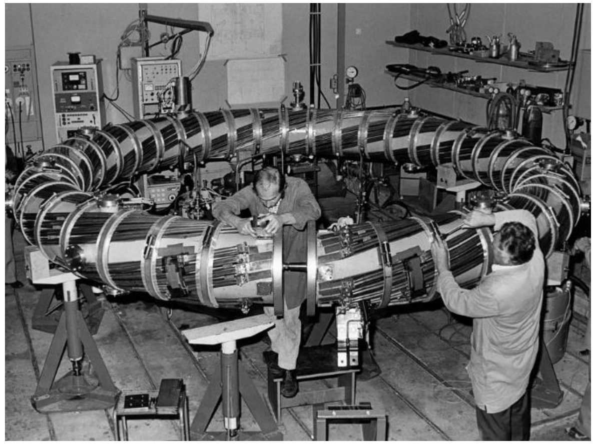
Predictions based on ISS04 scaling (Yamada 2004)



Other Experiments with similar parameters?

- The pre-predecessor of Wendelstein 7-X, called Wendelstein VII-A (1975 to 1985)
- R= 2 m
- a = 12 cm
- Equipped with a 70 GHz ECRH systems

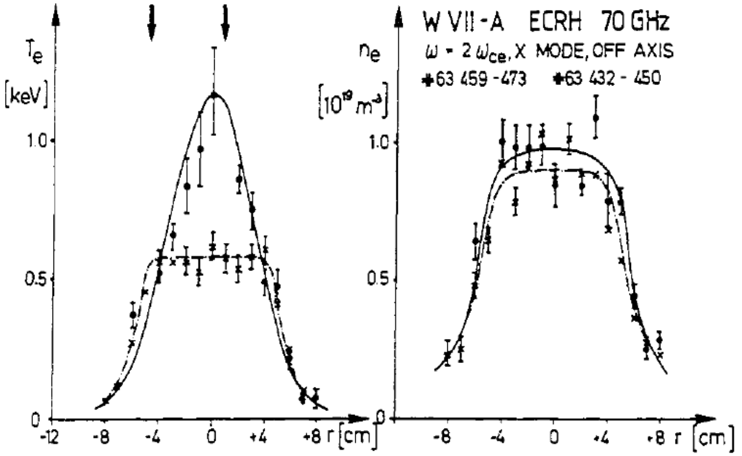
→ Ion temperatures in the range of 100 – 150 eV



	B_0 /T/	n_{eo} /10^{19} m^{-3}/	T_{eo} /keV/	T_{io} /keV/	W_p /kJ/	η_{exp}
28 GHz O-mode 1st harm.	1.0	0.5	1.2	0.15	0.15	0.55
		0.9	0.4	0.1	0.1	0.45
70 GHz X-mode 2nd harm.	1.25	1.1	1.0	0.15	0.25	0.8
		2.4	0.7	0.1	0.50	0.9

Table 1: Comparison of major plama parameters for 28 GHz first harmonic and 70 GHz second harmonic heating.

The total incident power was about the same for all data shown (170 - 180 kW).



V Erckmann *et al* 1986 *Plasma Phys. Control. Fusion* **28** 1277

Fig. 6: Electron temperature and density profiles for on-axis (solid line) and off-axis (dashed line) heating. The arrows indicate the position of the resonance layer $\omega = 2\omega_{ce}$.

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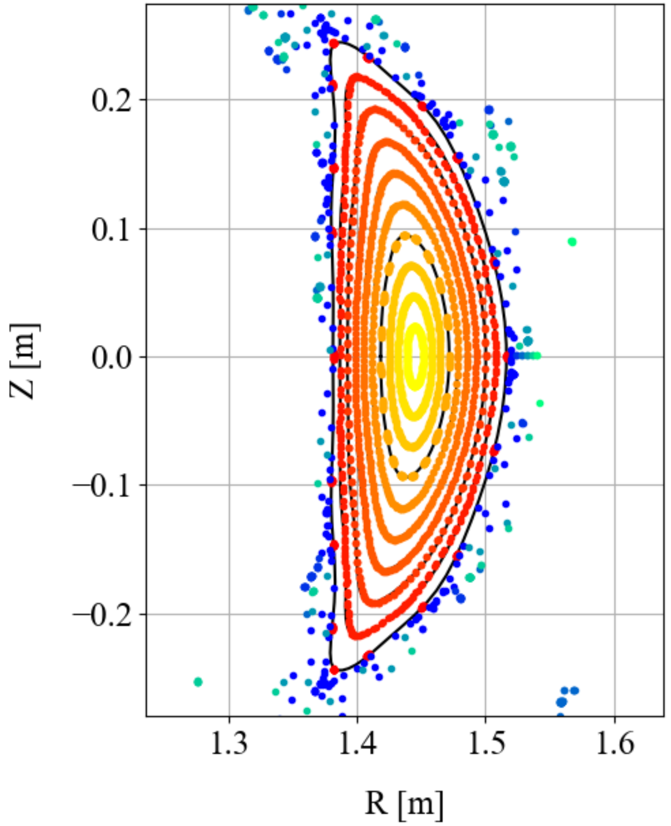


70 GHz gyrotron: 500 kW for 3 s

- Fabricated by CPI
- Delivered to IPP Garching in 2000 and operated at W7-AS until 2001.
- For 500 kW output power, it requires 55 kV, ~25 A (main power supply) and 25 kV for the depressed collector

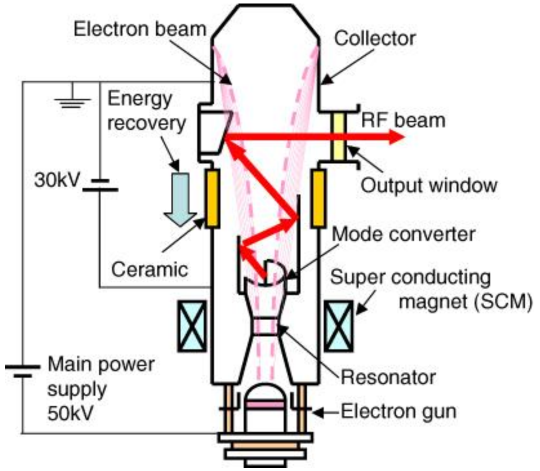
RESEARCH ARTICLE | OCTOBER 29 2001

Full performance ECRH experiments at W7-AS

G. Michel; H. Laqua; H.-P. Laqua; H. Maaßberg; N. Marushchenko; Ch. Fuchs; W7-AS Team

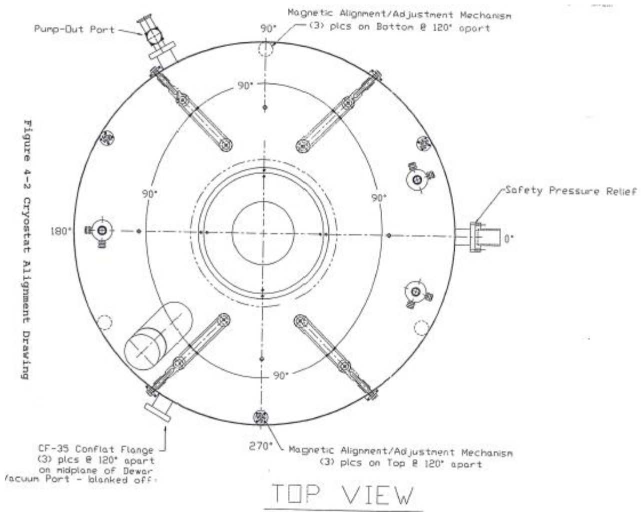
AIP Conf. Proc. 595, 354–357 (2001)
https://doi.org/10.1063/1.1424209

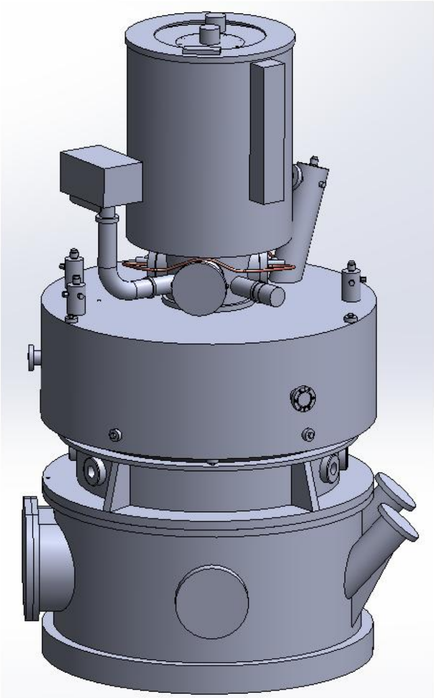
VGE-8071 70 GHz, 500 kW Gyrotron
Factory Test Protocol
February 22, 2000



Gyrotron Magnet

- Liquid helium cooled superconducting magnet
- Liquid nitrogen shield.
- Four coils with NbTi strains in a copper matrix
- B~2.8 T
- Alignment mechanism





CRYOMAGNETICS, INC.

OPERATING INSTRUCTION MANUAL
FOR
SUPERCONDUCTING MAGNET SYSTEM

Table 4-1

Main Cavity Field Profile Requirements

Position inches)	28 kG Flat (kG)	31 kG Flat (kG)	28 kG +2% Taper	28 kG - 2% Taper
-0.5	28.0 kG +/-0.14	31.0 kG +/-0.15	27.7 kG +/-0.14	28.3 kG +/-0.14
0.0	28.0 kG +/-0.14	31.0 kG +/-0.15	28.0 kG +/-0.14	28.0 kG +/-0.14
0.5	28.0 kG +/-0.14	31.0 kG +/-0.14	28.3 kG +/-0.14	27.7 kG +/-0.14
Cathode Z=-13"	1.8 kG +/-0.2	2.0 kG +/-0.2	---	---

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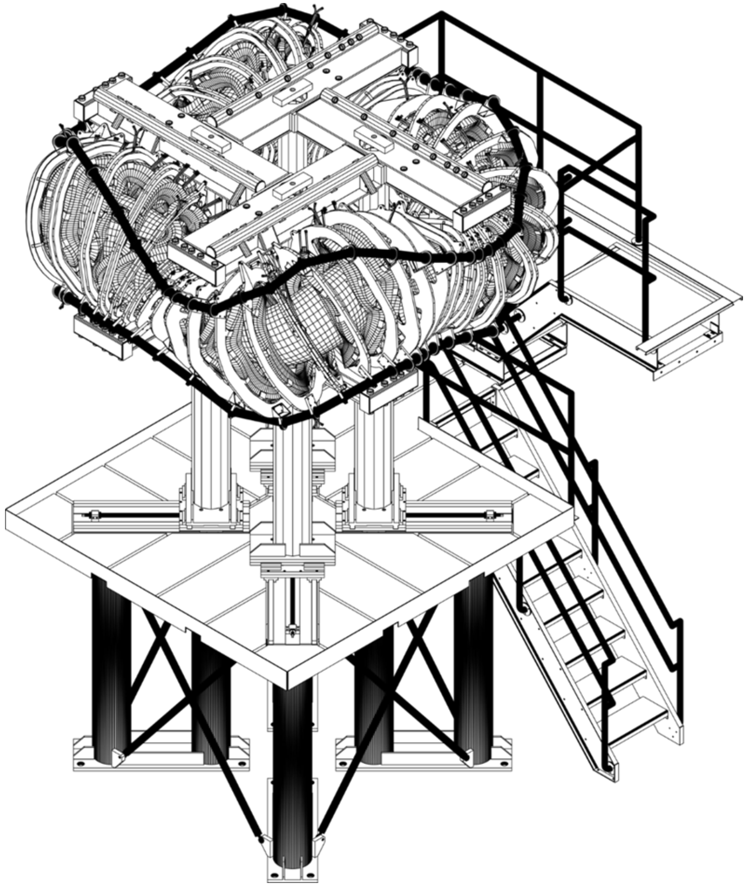
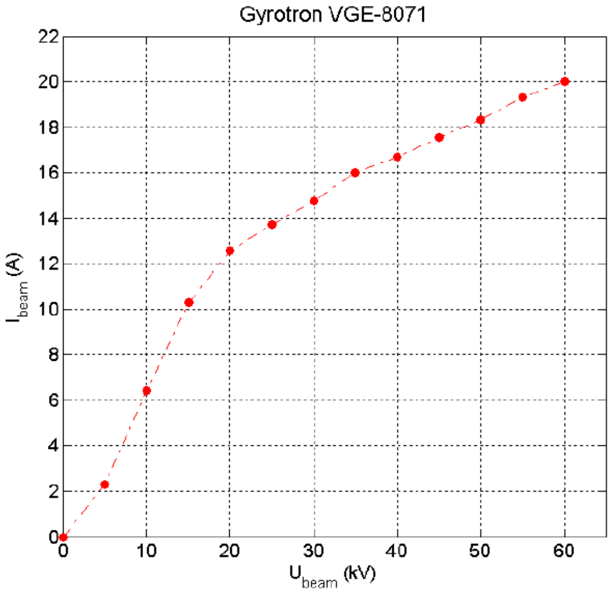


High voltage gyrotron power supply

- Aim for 300 kW operation
- 0 - 60 kV, 20 A
- Pulsed (100 ms every 3 min)
- Brake Switch system to shut-down in less than 10 µs to limit the injected maximum energy into the gyrotron to 10 J



Power supply from JEMA - Spain

HSX Helically Symmetric eXperiment

- Cost: $698k (in 2020)
- Input: 480 V 3-phase
- 14 power capacitor modules at ~1.3 kV
- 28 Booster converters

ID	Parameter	Value
1	Vout nominal	60kV
	Vout range	20-60kV
2	Minimum ramp-up/down time	100 μs
	Settling time	≤50μs
	Time delay	≤100μs
	Max overshoot	+/- 500V (at the output terminals of the PS)
3	Vout accuracy bandwidth	≤+/- 0.5% (+/-300V)
4	Vout steps	≤1kV
5	Vout ripple	≤0.5% peak to peak of nominal value (300Vpp)
6	Nominal output current	20 A
	Output current range:	0-20A
7	Fast Shutdown time	≤10 μs
8	Charge delivered into gyrotron in case of output short circuit or arcing in the gyrotron	<100mAs (<10 Joule)
9	Maximum pulse length	100 ms
	Minimum pulse length	2 ms
10	Maximum duty cycle	1/1800

Table 2.3. Functional parameters

Manufacturer	AVX
Model	FFLR6V0118KJE
Capacitance	1100 uF
Nominal voltage	1300 V
RMS max Irms	79 A @ 50ºC
Surge current (Is)	19800 A
Nº of capacitors in parallel	10
Datasheet reference	#Ref[9]

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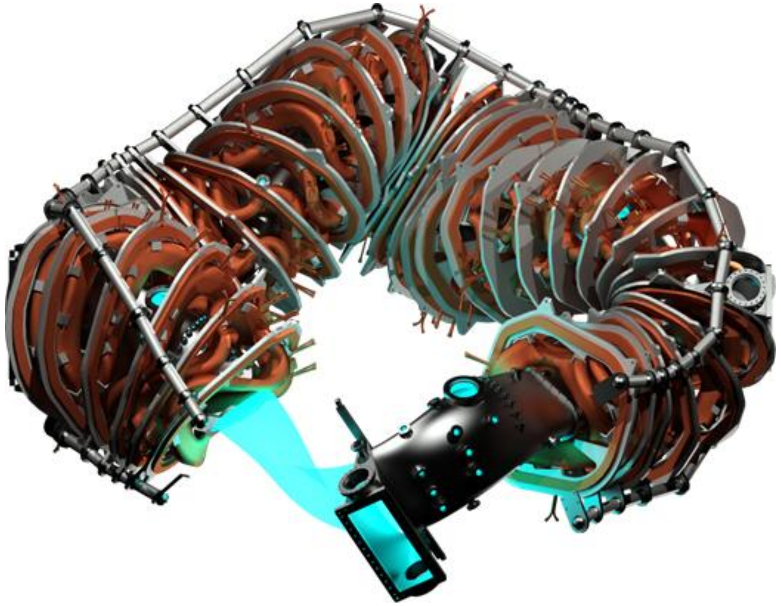
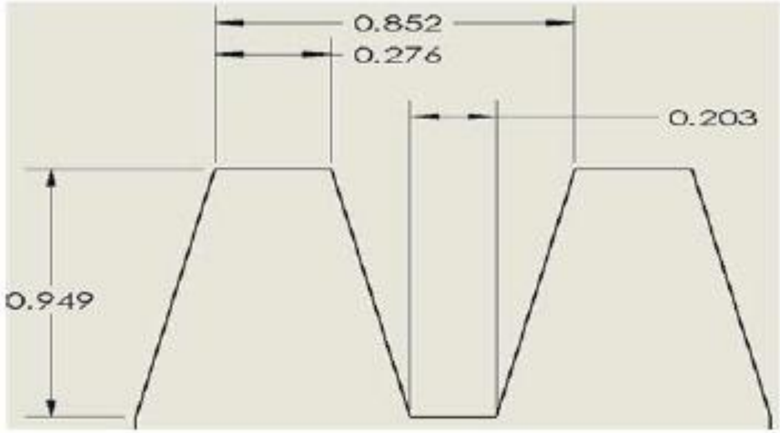


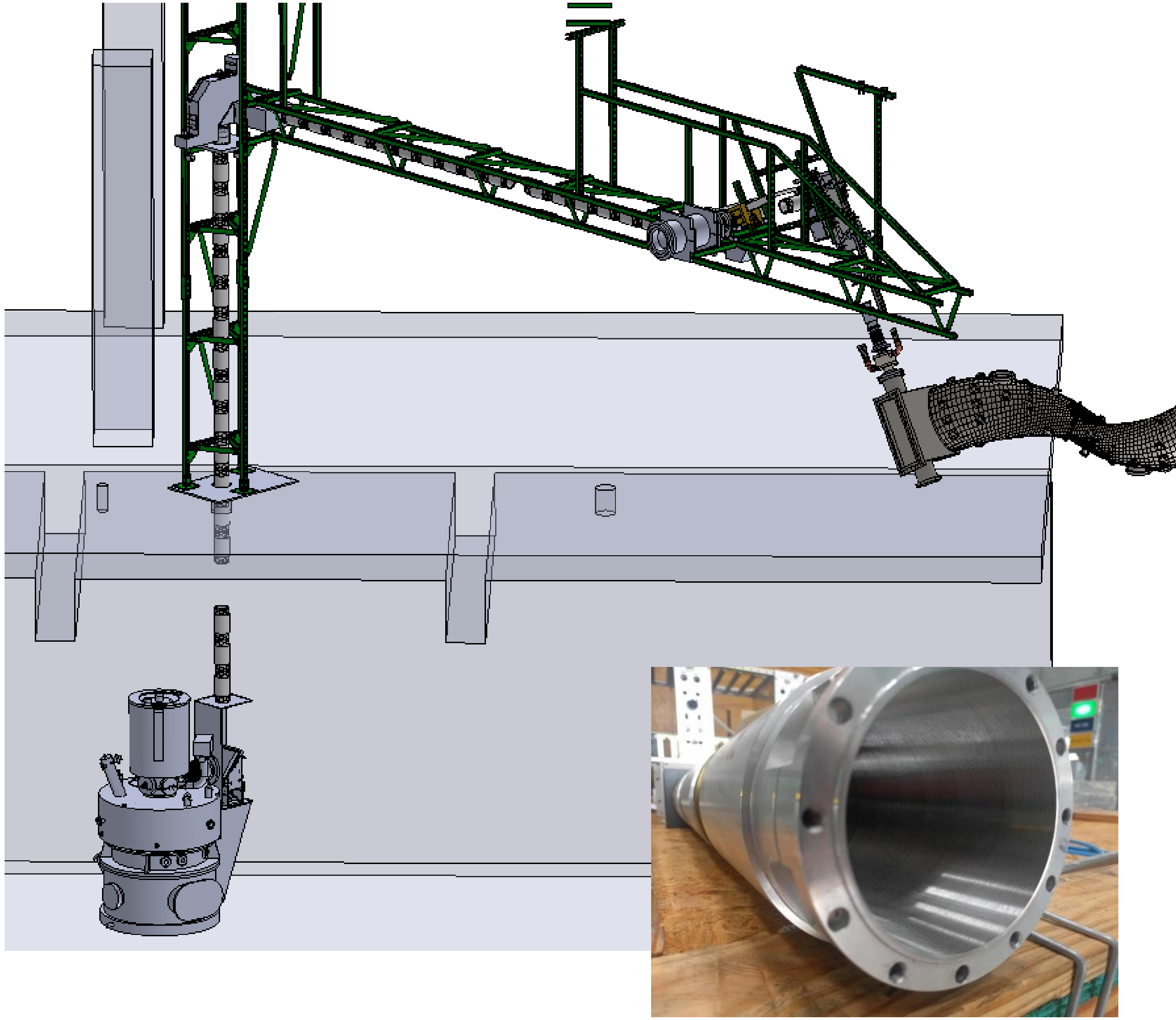
Gyrotron Transmission line designed by K. Likin

Transmission line based on corrugated waveguides (8.64 cm ID) provided by IPP Greifswald

- MOU close to gyrotron
- K-spectrometer
- 5 miter bends
- Dummy load
- Custom-made smaller waveguides (6.35 cm ID) from last miter bend to vacuum window

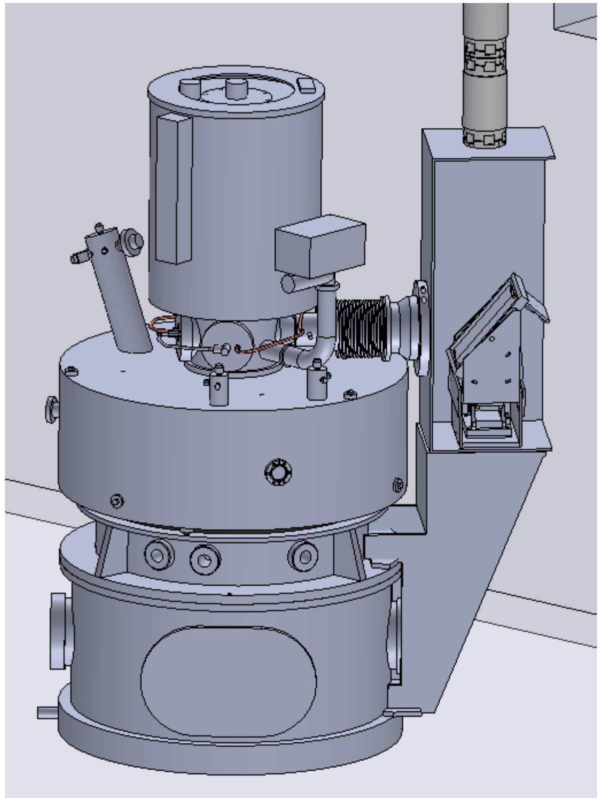


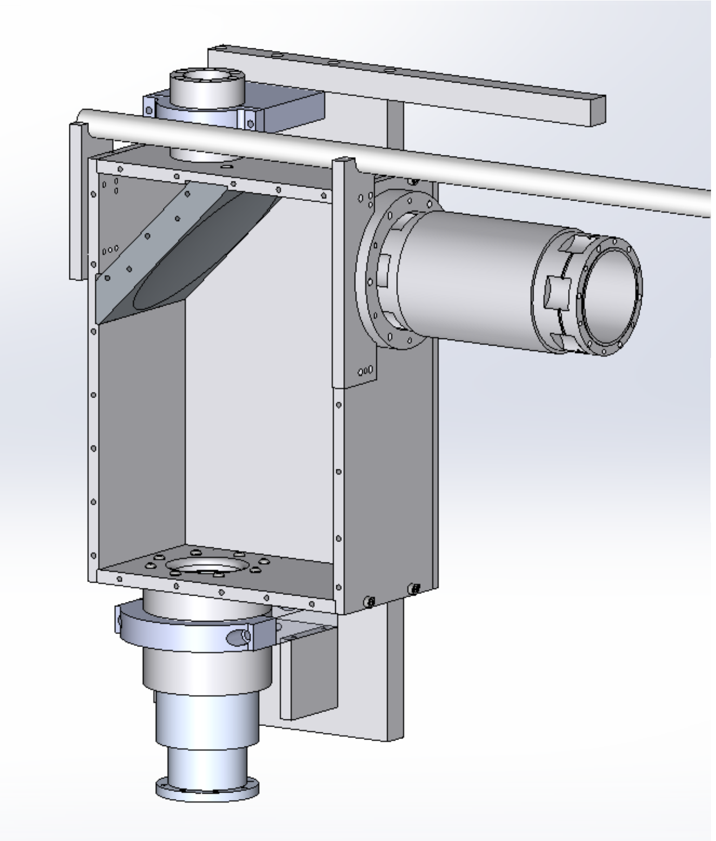
Corrugation of 8.64 cm ID waveguides in in mm

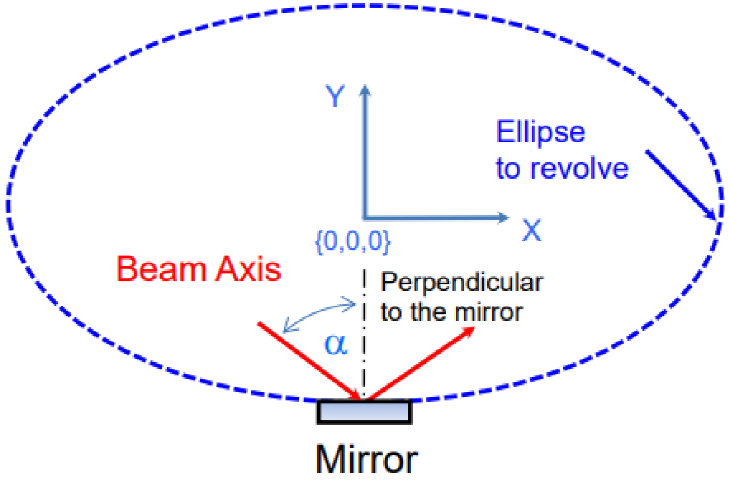


Use of ellipsoidal mirror to reduce losses

- Matching Optics Unit (MOU) based on one ellipsoidal mirror?
- Use of ellipsoidal mirrors in miter bends to minimize losses







IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 30, NO. 3, JUNE 2002

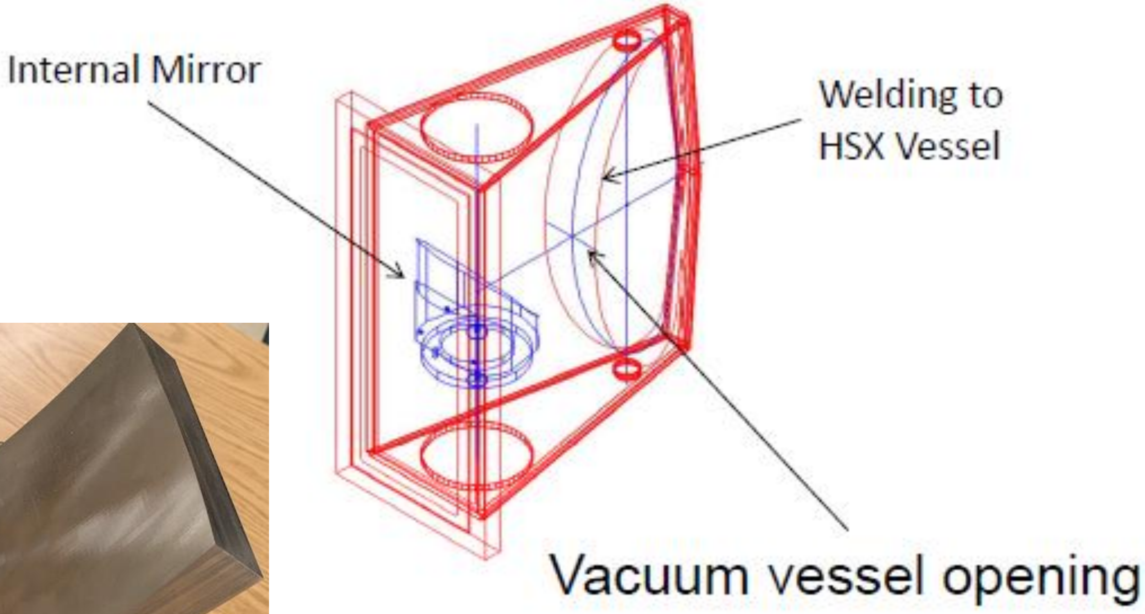
Passive High-Power Microwave Components

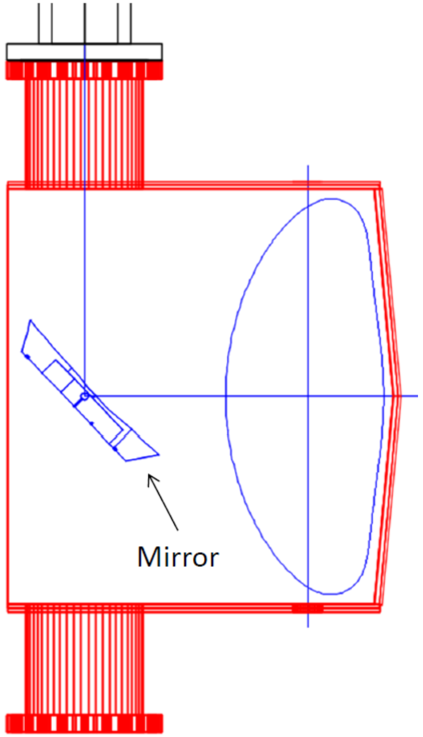
Manfred K. Thumm, *Fellow, IEEE,* and Walter Kasparek

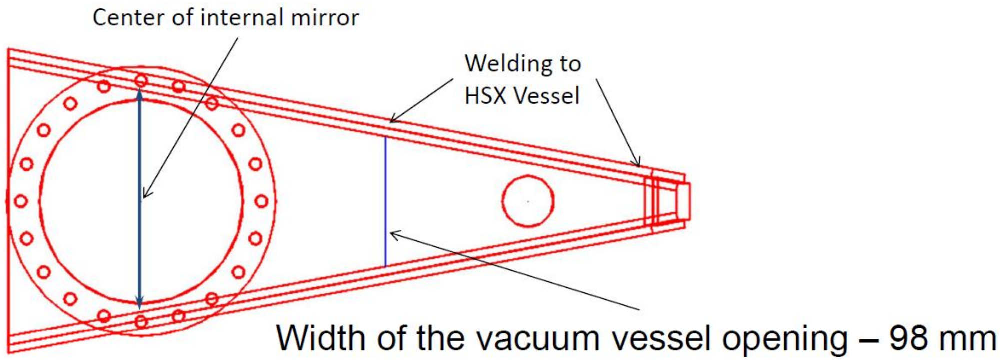
Designs by Konstantin Likin

Beam shape to fit into the HSX vacuum vessel and avoid overheating of the mirror

- 5 cm beam width
- 5-degree cone







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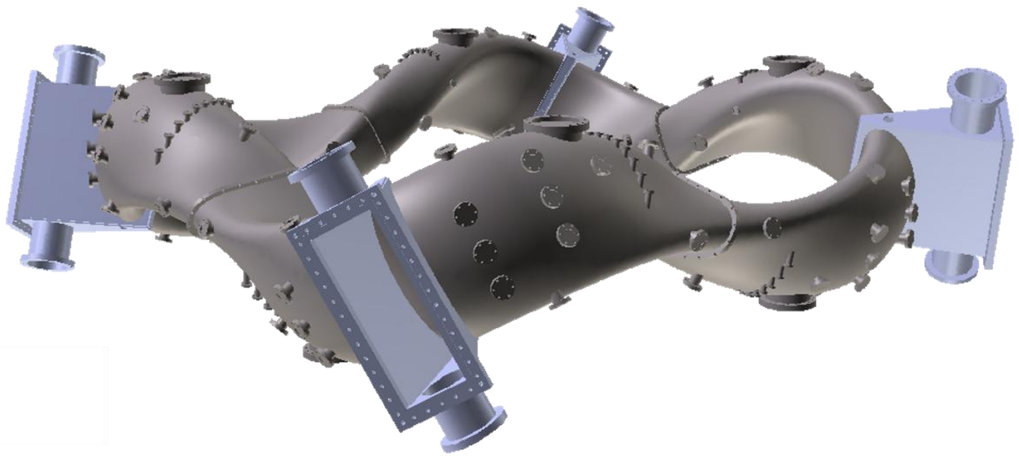
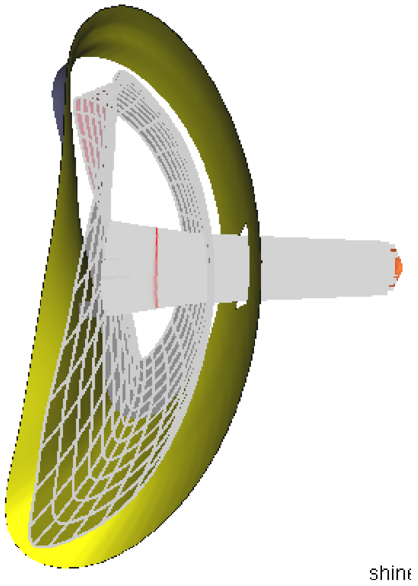
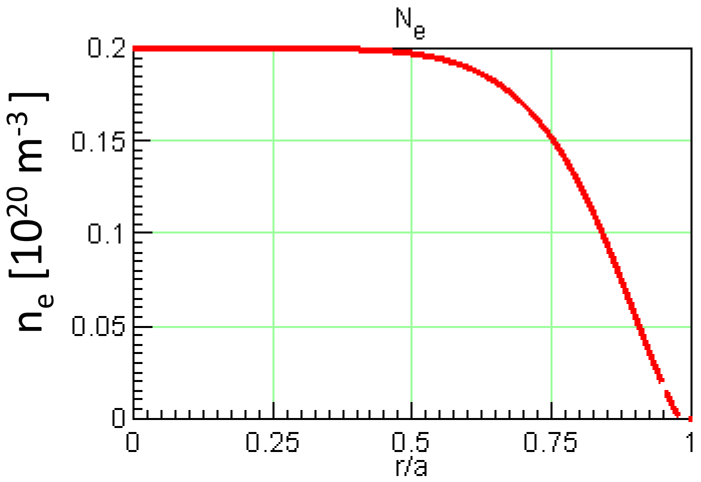


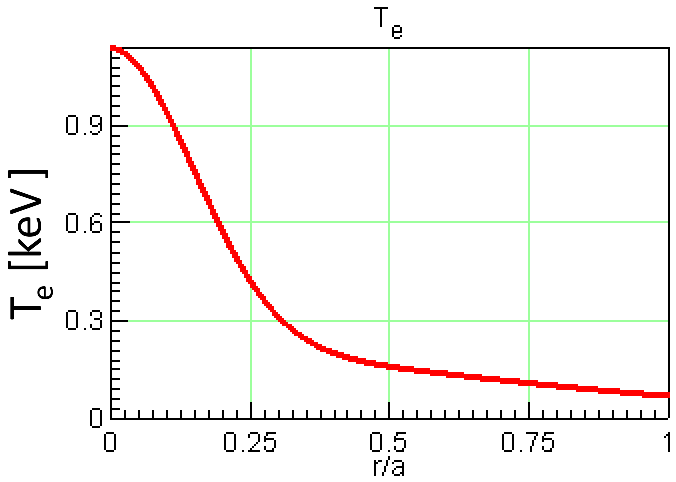
TRAVIS (2018a) modelling

- TRAVIS ray tracing code employed at HSX
- Consider 5 cm diameter beam with a cone of 5 degrees
- Simulation of 31 rays
- Consider typical HSX profiles shapes
  - T_e > 1 keV
  - Peaked n_e and T_e profiles



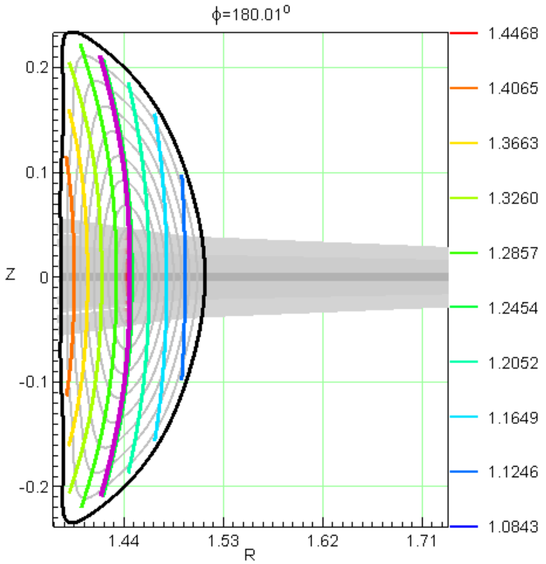
Marushchenko N.B., Turkin Y. and Maassberg H. 2014 *Comput. Phys. Commun.* **185** 165

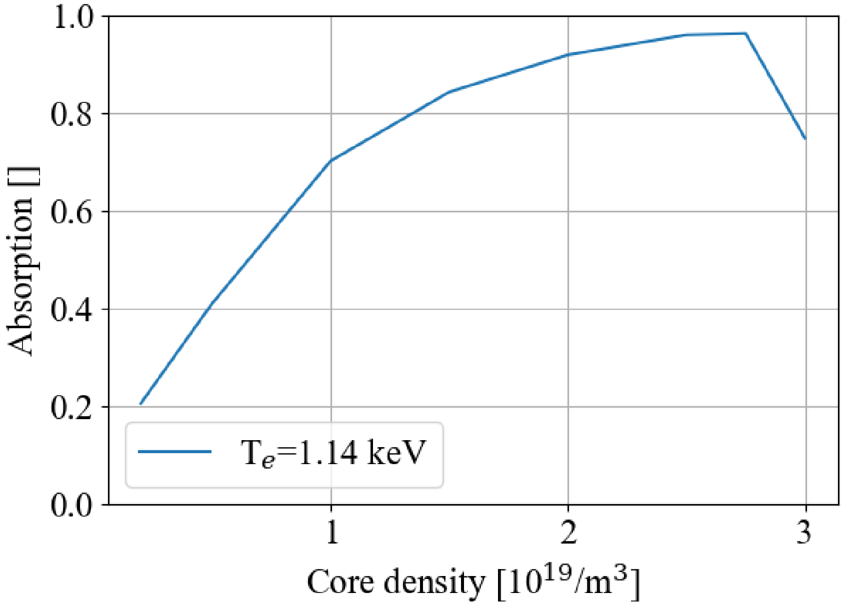


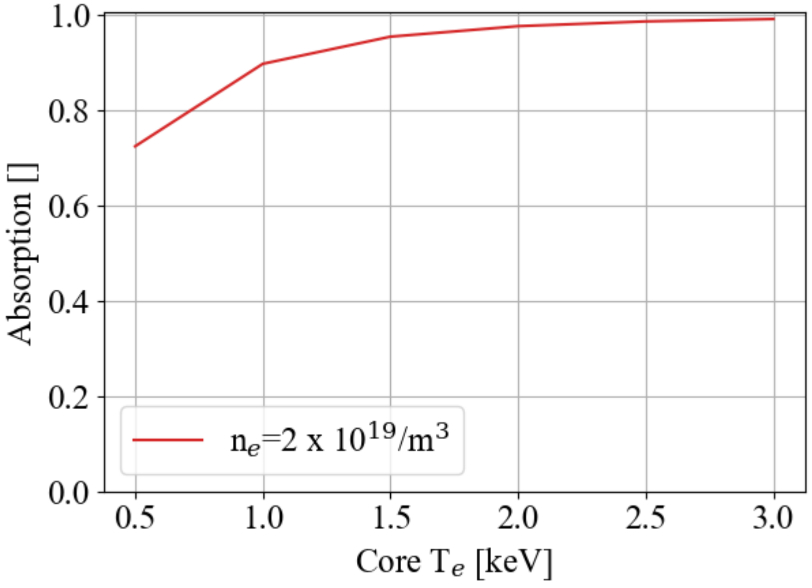


X2 – mode heating provides excellent absorption

- X2-mode heating with 70 GHz
- High absorption >50% for a large range of temperatures and densities
- Operation new cut-off might be possible

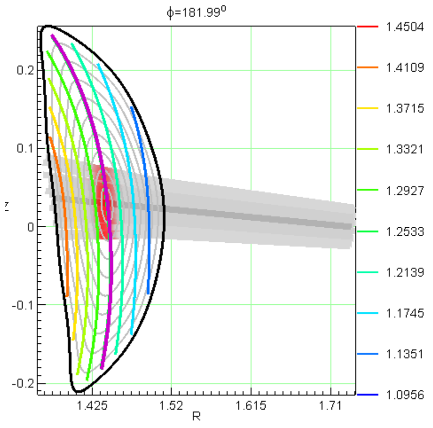


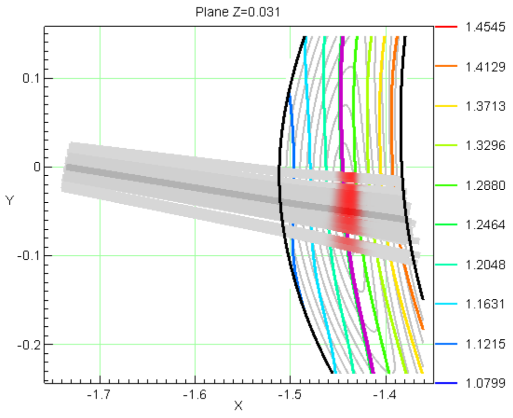


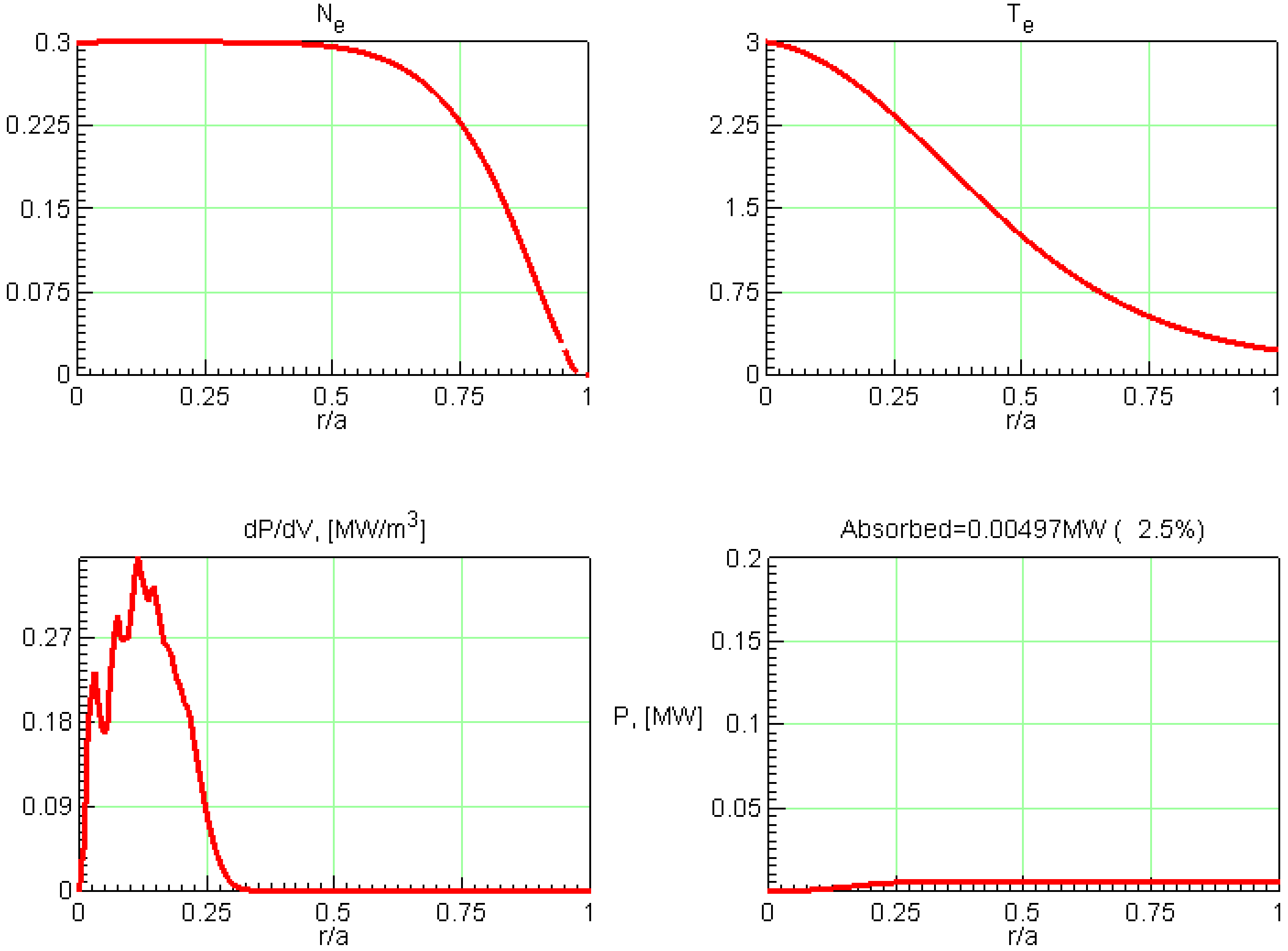


O2-mode heating is very limited

- O2-mode heating at 1.25 T has a cut-off density of **6.0 x10^{19} /m^3**
- However, only weak absorption predicted by TRAVIS for 3 keV plasma
- 2.5% single pass absorption for perpendicular launch
- 12% single pass when considering 2-deg angle (X-mode contribution)







Summary & Outlook

- HSX currently installing a 70 GHz gyrotron
- System will deliver 200 kW for 100 ms
- Density operation with $n_e > 2 \times 10^{19}/m^3$ possible
- Expected first 70 GHz plasmas mid of next year

Thank you!