Large Scale CW ECRH Systems: Meeting a Challenge

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{ High Power and Versatility *(increasing complexity)* } vs. { High Reliab. Avail. Maint. Inspect. *(robustness and simplicity)* }

The advanced ECRH Plant:

- *sources*
- *transmission*
- *in-vessel components*

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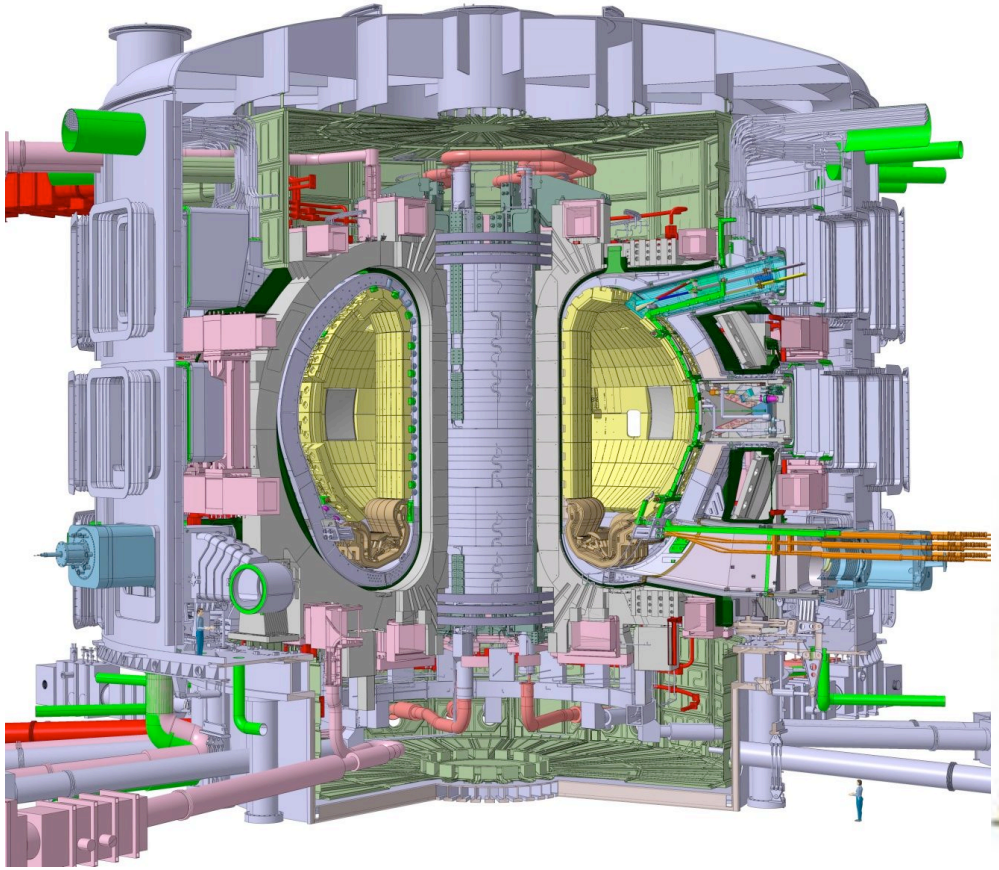
Next Step superconducting Fusion Devices

Tokamaks

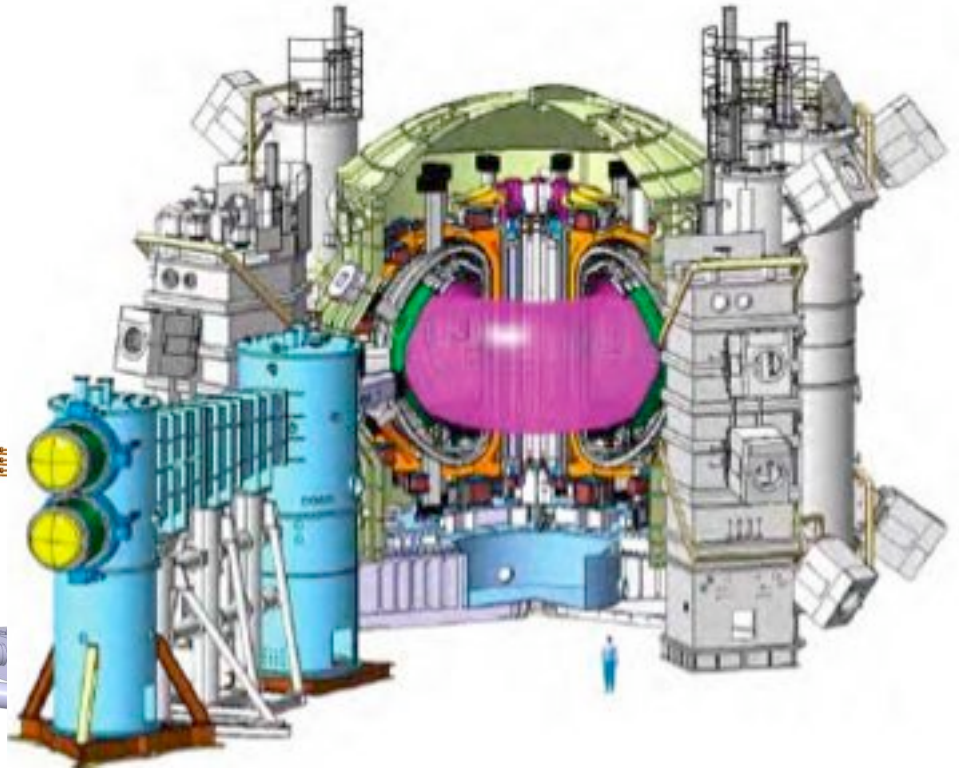
ITER

the flagship

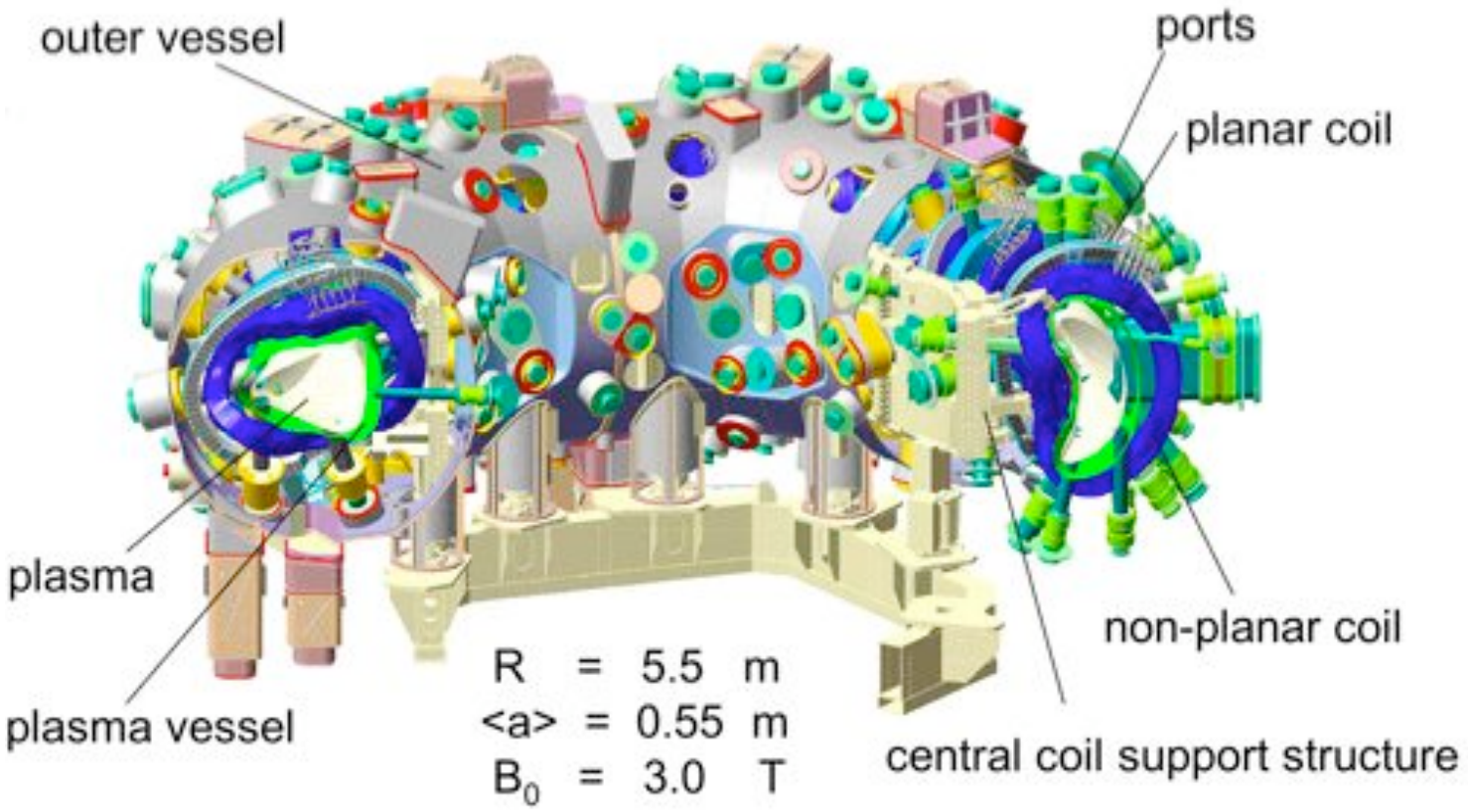


JT-60SA

‚broader approach‘



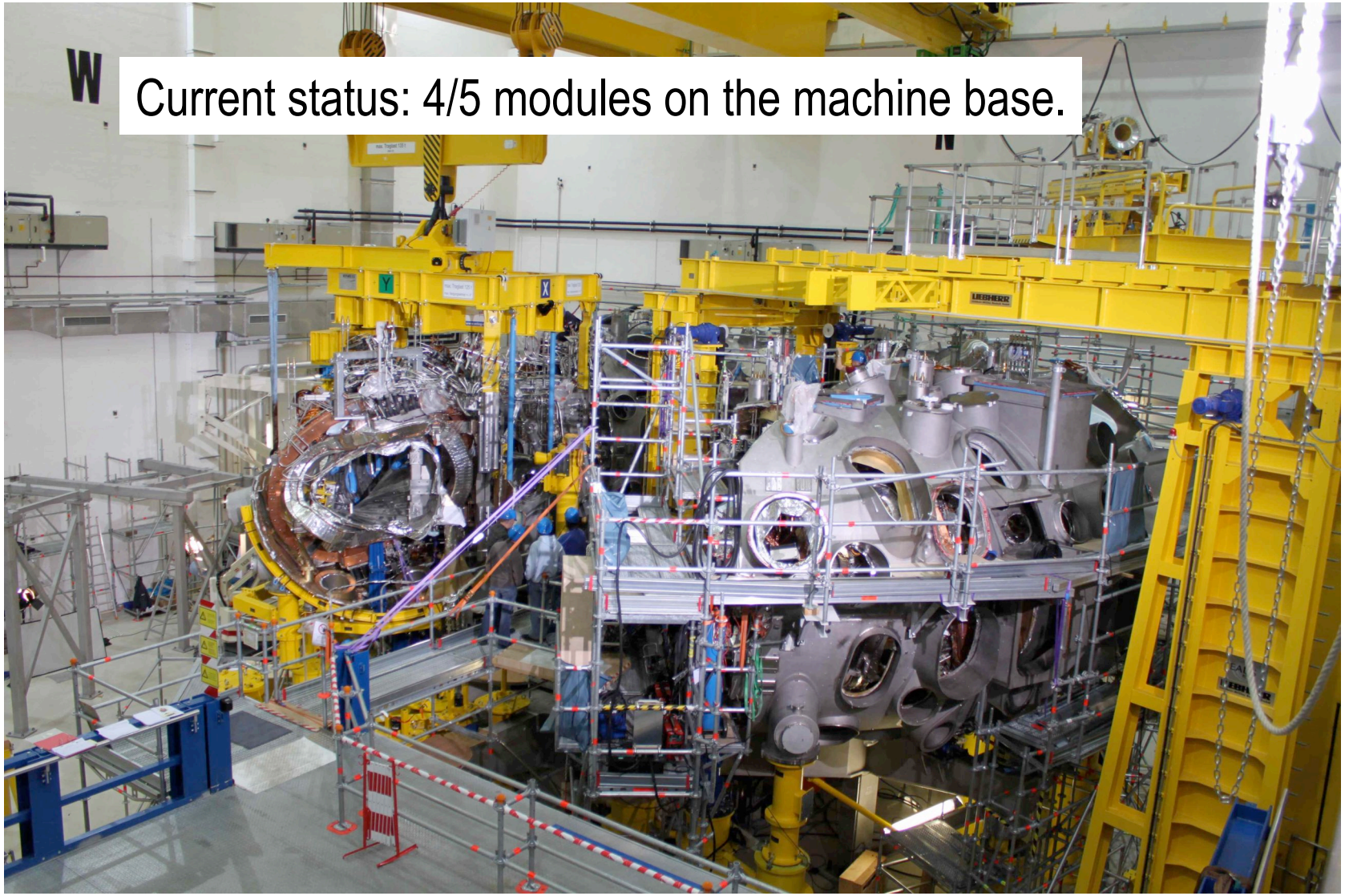
The W7-X Stellarator: exploring the alternative route



- Inherent steady state capability
- Confining magnetic field generated by external coils only

W7-X: Hands-on support during assembly

W7-X: Module Assembly



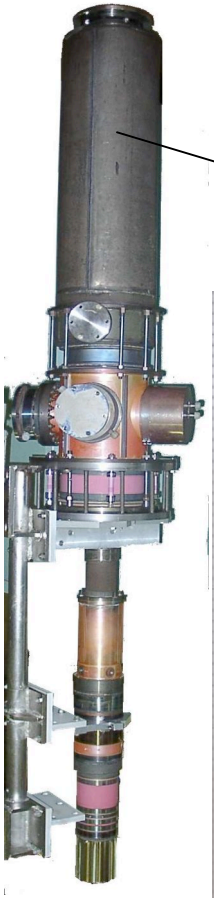
ECRH for W7-X and for ITER...

.....is a ‚day one' Heating & Current Drive System

	W7-X	**ITER**
Power (MW)	9 (10 inst.)	20 (24 inst.)
Power per Gyrotr. (MW)	1(140 GHz) 0.4 (104 GHz)	1 (2)
Frequency (GHz)	140/104	170
Operation Mode	2nd Harm. (2.5 T) CW (1800 s)	1st Harm. (5.4 T) CW (1000 s)
Transmission	optical	waveguide
Launcher	Front steering/Remote steering	Front steering
Physics demands	Plasma start up	Start up assist (127 GHz)
	Bulk Heating and Current Drive	Bulk Heating and Current drive
	q-profile shaping	q-profile shaping
		MHD-control
	Net-current suppression	Net-current enhancement

CW-Gyrotrons in the MW power range...

...are the back-bone of next step ECRH systems



The ITER-Gyrotron: 170 GHz

IAP Nizhny Novgorod/GYCOM
(1.02 MW, 570 s)

JAEA/ TOSHIBA
(1 MW, 800 s)

The W7-X-Gyrotron: 140 GHz

FZK, CRPP, THALES
(0.92 MW, 1800 s)

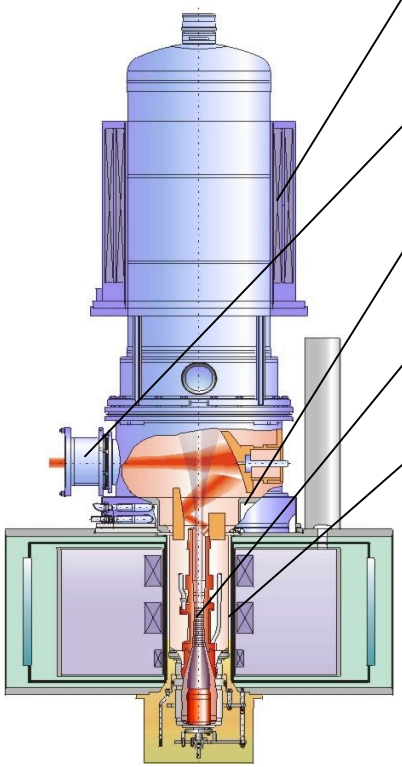
US/CPI (0.9 MW, 1800 s)

...these are prototypes,
series production remains a challenging task

W7-X Gyrotrons: R&D from prototype to series tubes

Prototype R&D successfully terminated in 2004,
first Series Tubes from TED and CPI successful in 2005 (>900 kW, 1800 s)

...since then....

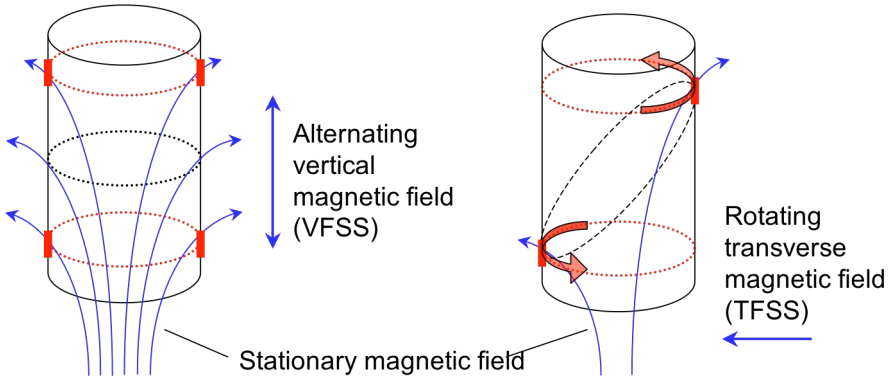


...improve Collector sweeping, vertical + transverse 50 Hz, smooth power distribution

Diamond Window,
...replace Water- by Oil-Cooling,
(prevent long term corrosion)

...improve body-isolation (+ 30 kV)

...improve e-beam tunnel,
suppress parasitic oscillations

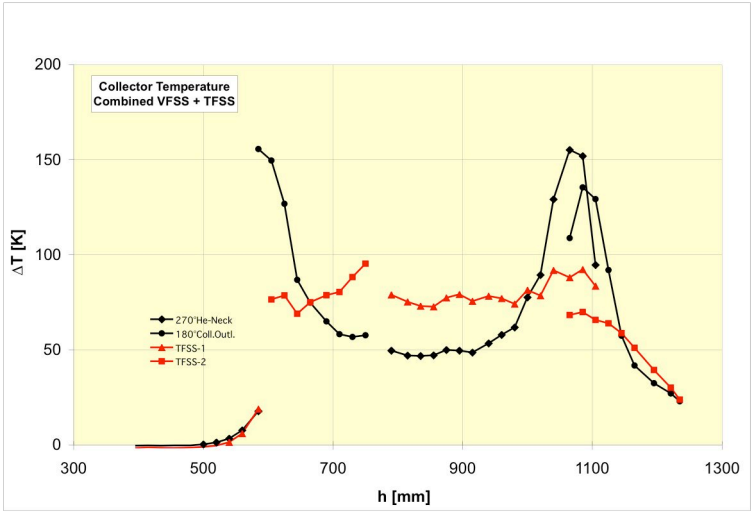


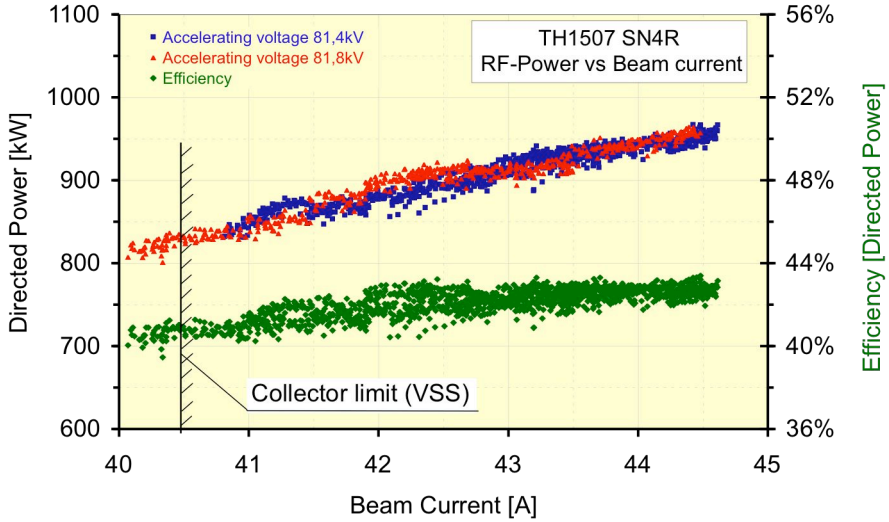
...reduce RF-absorption in gyrotron shaft, temperature rise 7 deg/min, limits pulse duration to < 30 min, cooling difficult, restriction on repetition rate

High power operation, TED-Gyrotron SN4R

Advanced Collector Sweeping removes Collector Loading Limit

- Vertical Sweeping at Collector
  - > strong power peaking at turning points
- Collector loading limited to 1.3 MW
  - > determined by peak-loading
  - > determines output power at given efficiency (40 - 45 %)
- Advanced Sweeping (IPP-KIT-patent)
  - > flat distribution
  - > Peak loading reduced to 62 %
- Plenty of margin to increase input power (Beam Current) at the given efficiency
  - > increase rf output power
  - > still margin for higher current (power)

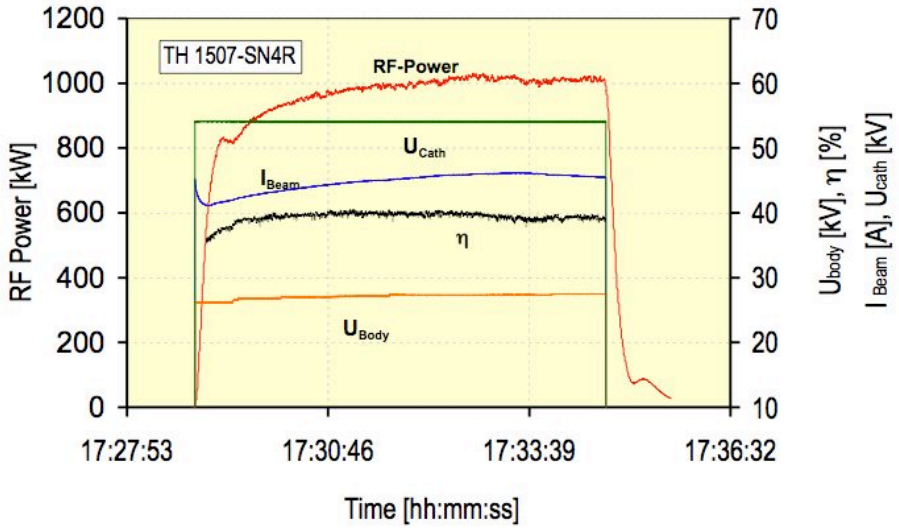




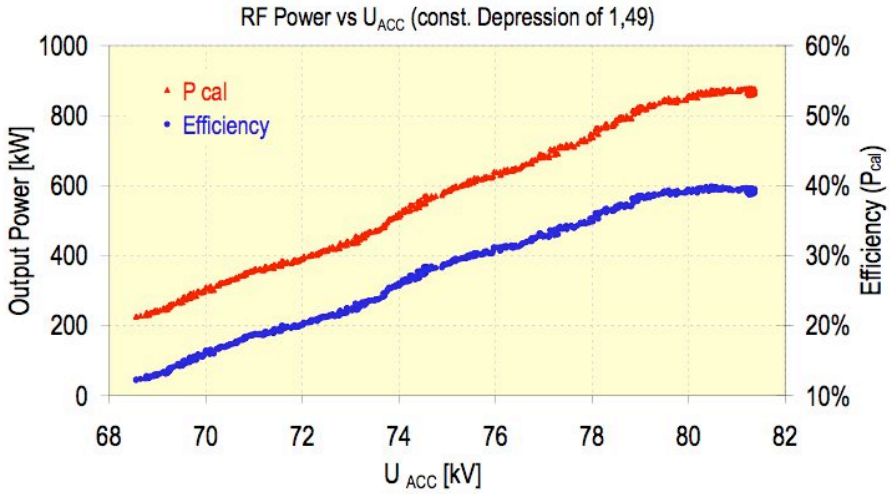
High power operation, TED-Gyrotron SN4R

Advanced Collector Sweeping removes Collector Loading Limit

- obtain > 1 MW directed power at Gyrotron window
- still margin to go to higher current, PS can handle 50 A



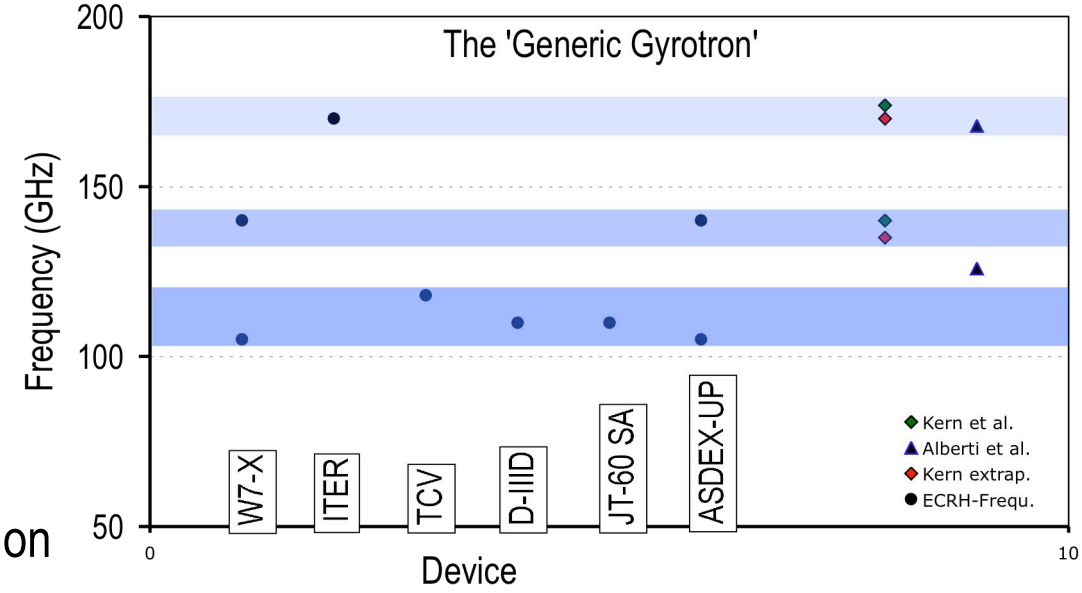
- good power control
  200 kW < P < 900 kW
- tune U_{ACC} at constant depression ratio
  > quasi adiabatic (10 min)
  > fast, up to 10 kHz



The ‚Generic Gyrotron‘

- different devices have individual gyrotron frequency and related long term R&D
- all gyrotrons operate at the limits (with reduced reliability)
- painfull process toward ‘series’ production
- small market for industries, few tubes of the same kind only

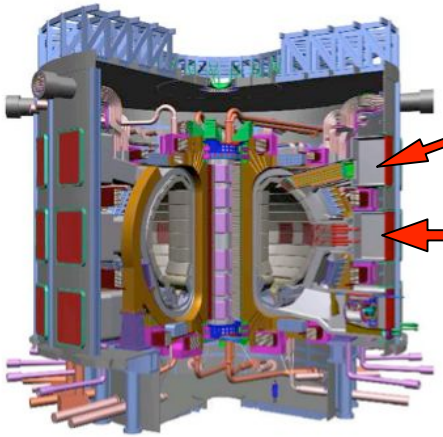
→ *Generic 3f-Gyrotron*
based on single disc CVD-window
satisfies the needs of different devices
within some acceptable (?) margin



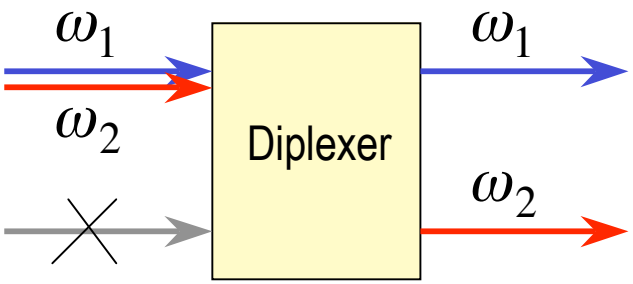
	f (GHz)	Mode	Window
Kern et al. based on W7-X Gyrotron	**104**	TE 22,6	1.8 mm, 3 λ/2
	140	TE 28,8	4 λ/2
	174	TE 34,10	5 λ/2
Alberti et al. based on W7-X Gyrotron	**126**	TE 26,7	1.49 mm, 3 λ/2
	168	TE 35,9	4 λ/2
IAP/GYCOM for ASDEX-UP	**104.7**	TE17,6	1.8 mm, 3 λ/2
	139.6	TE22,8	4 λ/2

Transmission: ECRH-Systems need beam switches...

...and beam combiners to simplify power upgrades

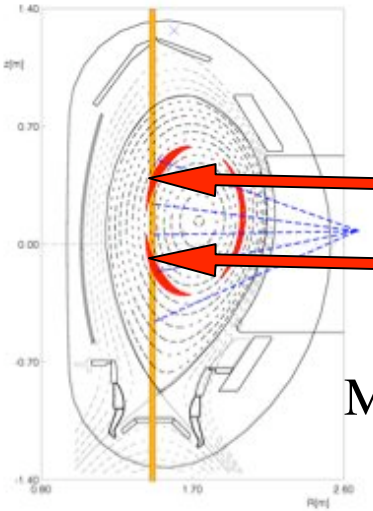


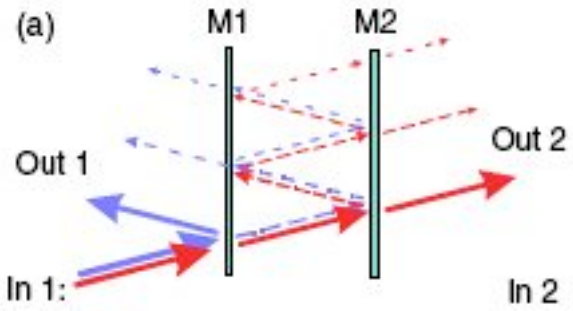
switches between upper and equatorial launcher



M. Petelin et al. IRMMW 2006
W. Kasparek et al. NF 2008

MHD-control
switching in phase
with island rotation 3-10 kHz
increase (double) efficiency

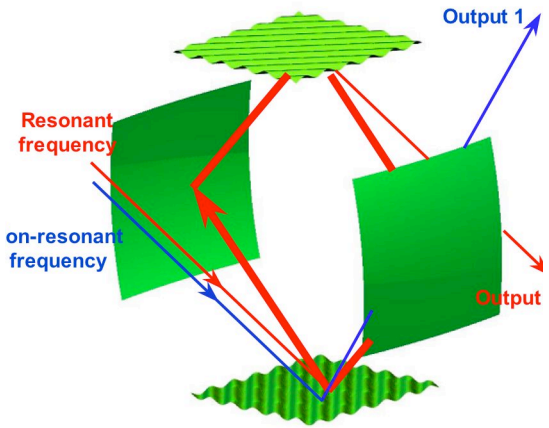




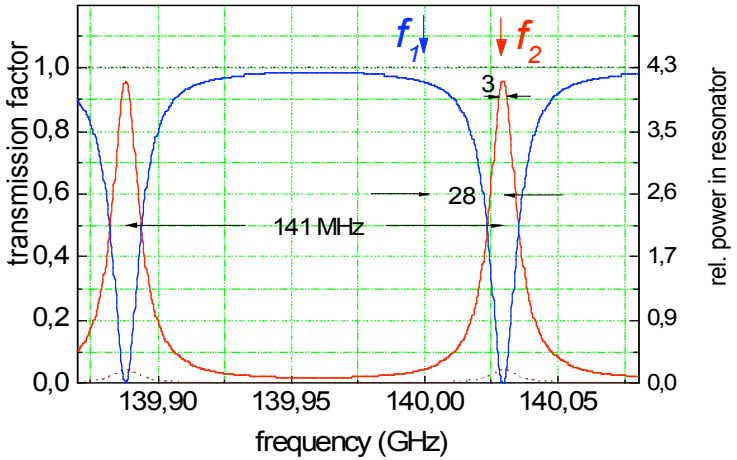
Mechanical switches are slow,
undefined beam location during switchung,
turn off power during switching

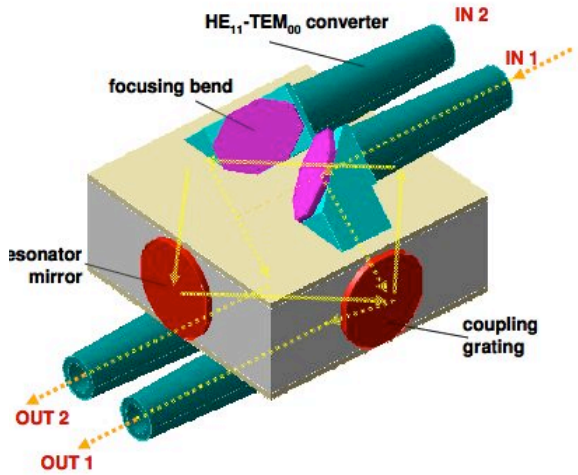
QUO-FADIS and Combiner: The waveguide based Diplexer

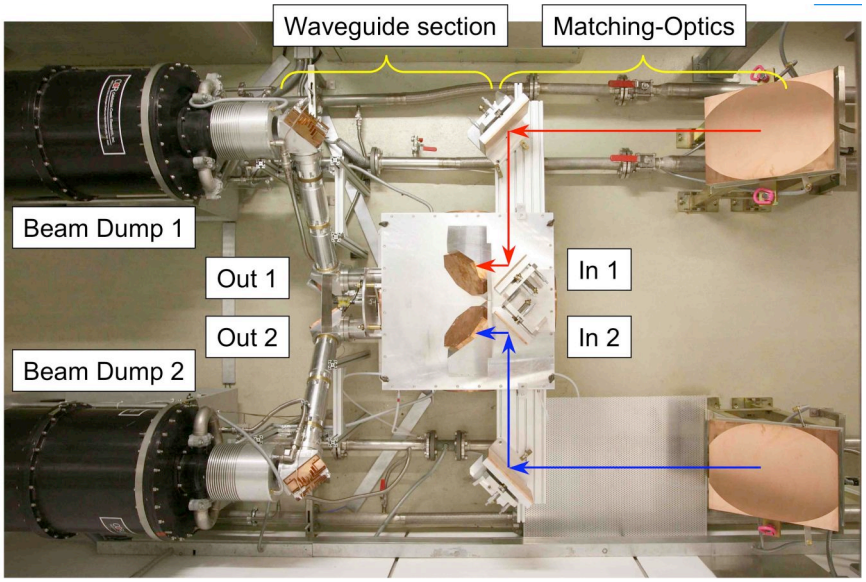
Designed for integration into the transmission system of ASDEX-UPGRADE



$$\Delta\omega/\omega \approx 10^{-4}$$

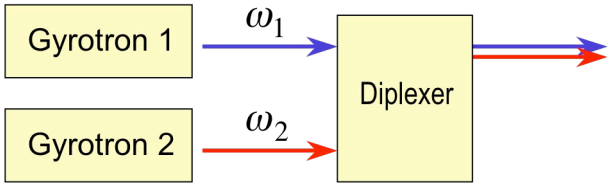




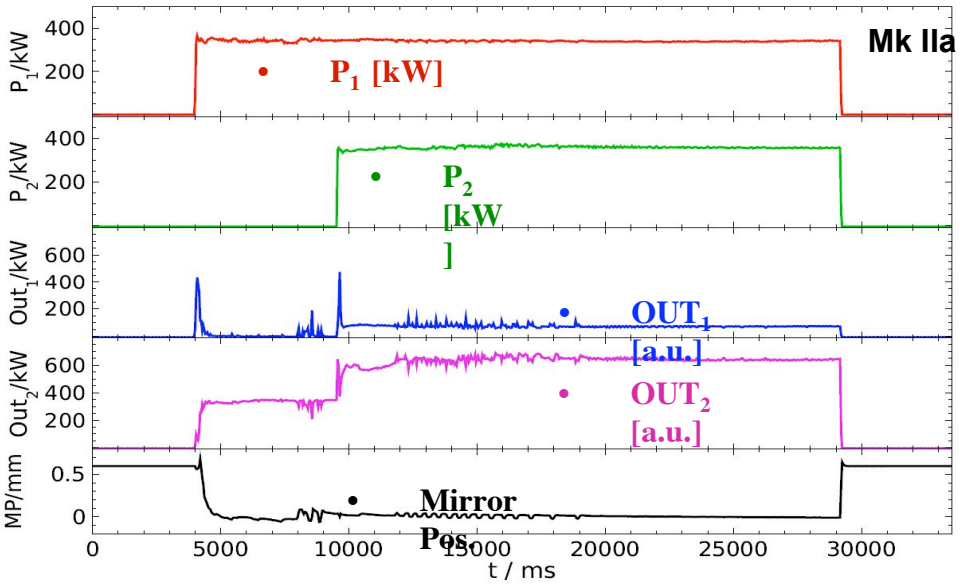


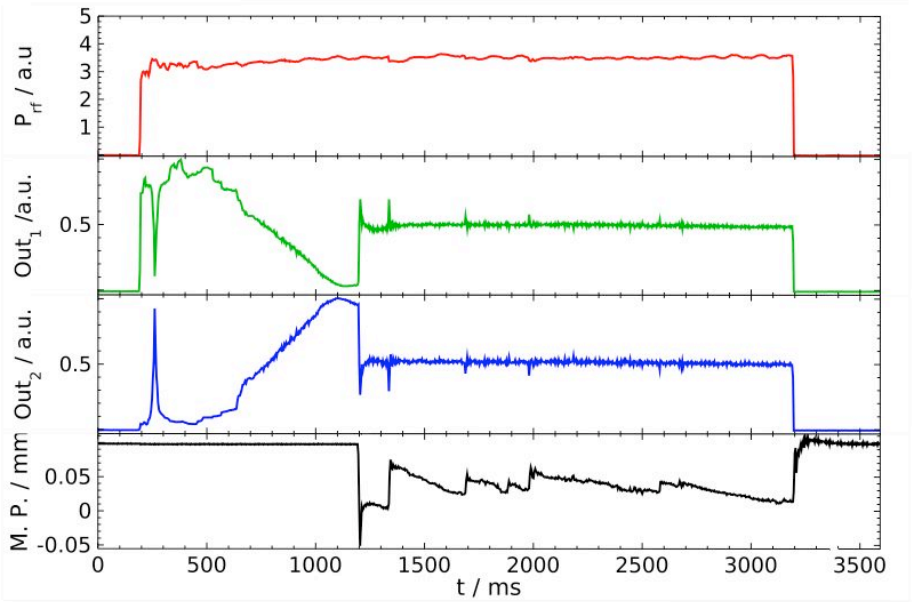
ECRH: Diplexers for power distribution

- Operate 2 Gyrotrons with Δf = 40 MHz
- Power combination: IN1+ IN 2 → OUT2
  - → Reduce number of transmission lines



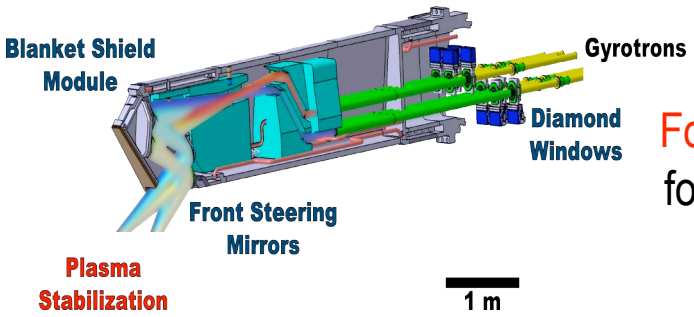
- Power splitting between launchers
- slow switching (between Launchers)
  - → tune diplexer
- fast switching (MHD-control)
  - → tune gyrotron





In Vessel Structures: Launchers for W7-X and ITER

Plug-in Front Steering Launchers

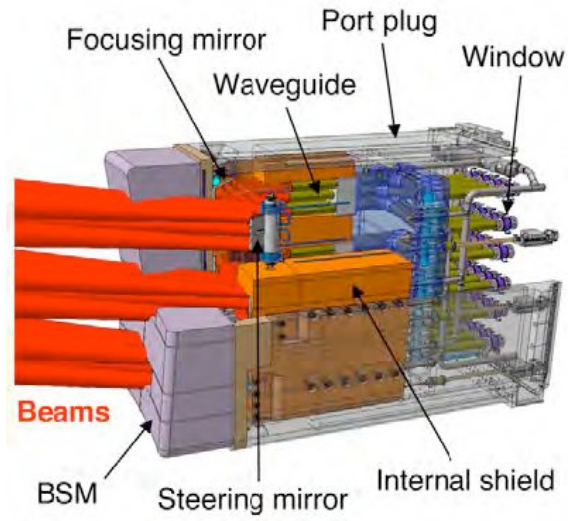


ITER

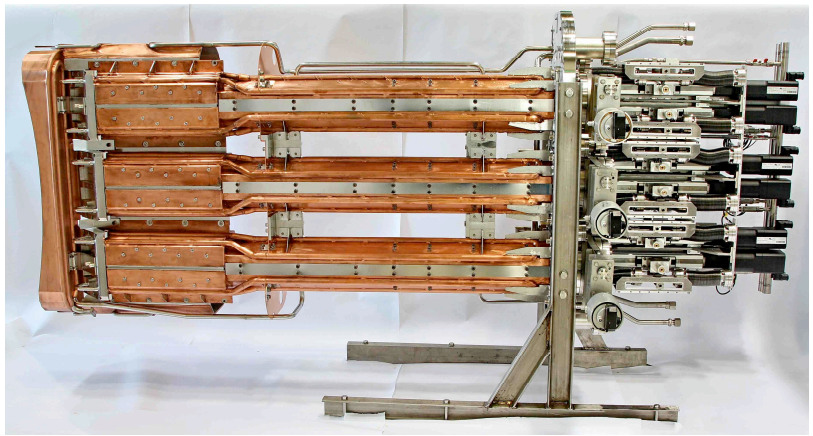
Four upper launchers
for MHD-stabilization
(6) 8 waveguides
per port
ECRH-power /Port area:
10.5 (21) MW/m^{-2}
EU-task

W7-X

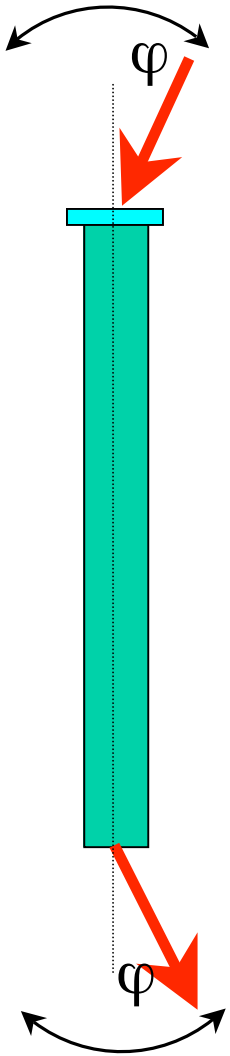
Four equatorial ports
3 RF-beams per port (2 spare)
Wide steering range
(O2, X3, O-X-B, CD)
toroidal < 35° , poloidal < 30 °
ECRH-power /Port area:
8.5 (17) MW/m^{-2}



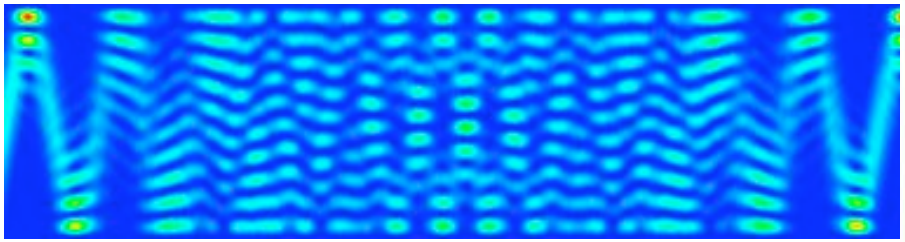
One equatorial port
for Heating and CD
24 waveguides
Steering of 8 comb. beams
20 - 45 deg (tor)
JA-task



ECRH: The Remote Steering Launcher

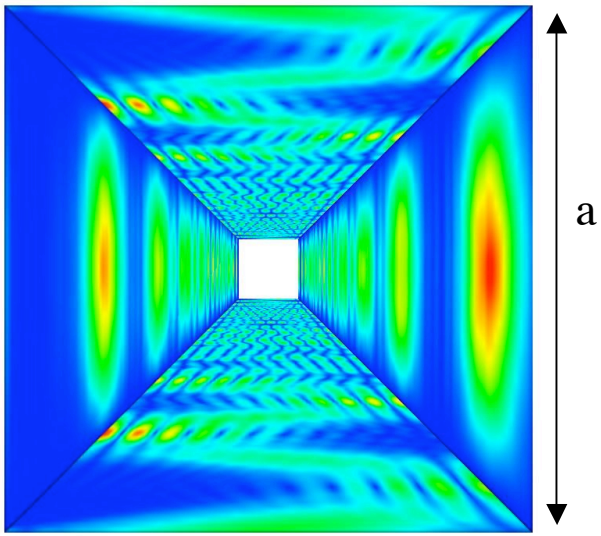


- Input wave-beam is transformed to an (inverse) output wave beam in a square corrugated waveguide (dim. a) of length $L = 4a^2 / \lambda$
- Remote beam steering possible outside the vacuum vessel
- Simple and compact solution, high power density
- No movable in-vessel mirrors, preferred solution for DEMO
- R&D for 1 MW, cw at W7-X, high-field side launch (narrow ports)



Calculated Wave Pattern in the waveguide

Plaum et al. J.Phys 2005



The Remote Steering Launcher: High Power Tests:

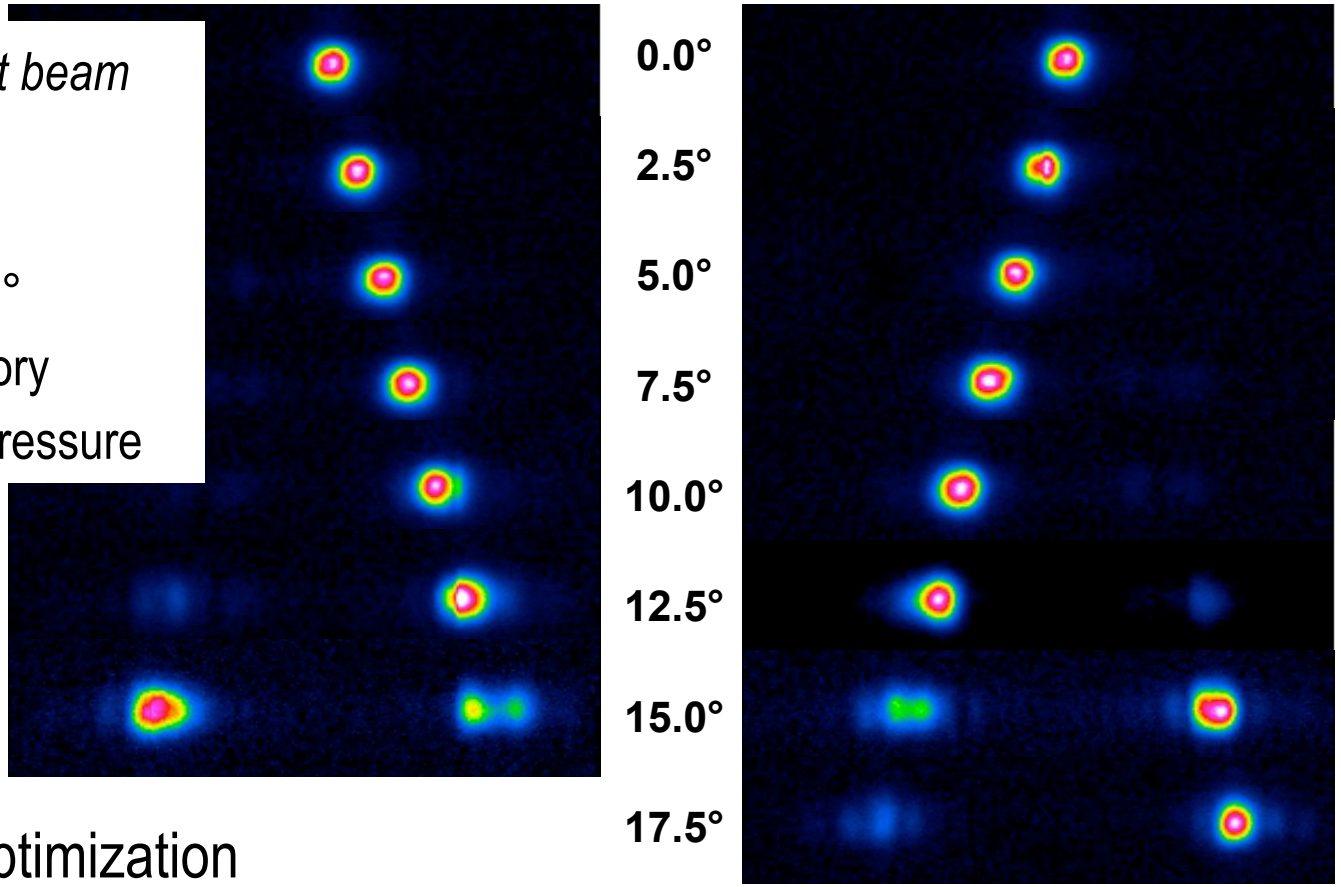
Measured Radiation Patterns of the Output Beam

Parameters:

140 GHz, L = 6.62 m, a = 60 mm, distance from waveguide mouth: d = 2.375 m, parallel polarization

Angular Scan of the input beam

- good beam quality
- steering range +/- 12 °
- in agreement with theory
- 700 kW/10 s at atm. pressure

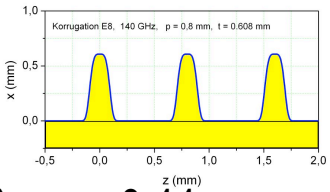


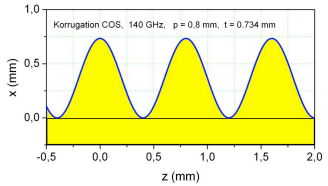
→ Room for optimization

Remote Steering Launcher for W7-X

Optimization of waveguide properties

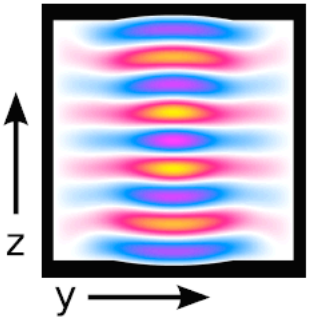
- Reduce transmission losses
  (optimize corrugation profile)

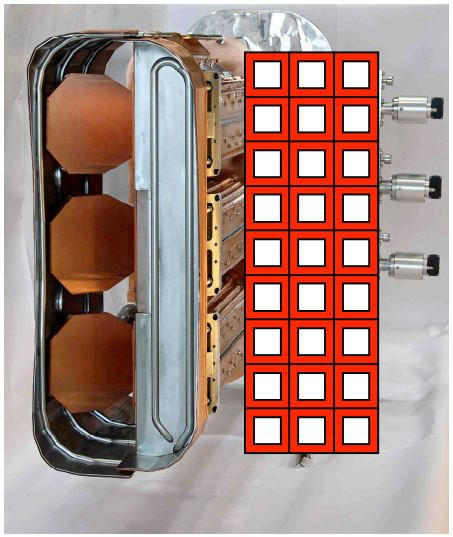




Rel. Abs (comp. to back-reflection from a plate): 0.44 0.52

- Mitre bend with ≠ 90 deg
- Minimize gap lossses, optimize position for insertion of vacuum valve
- optimize waveguide shape to extend the angular scanning range





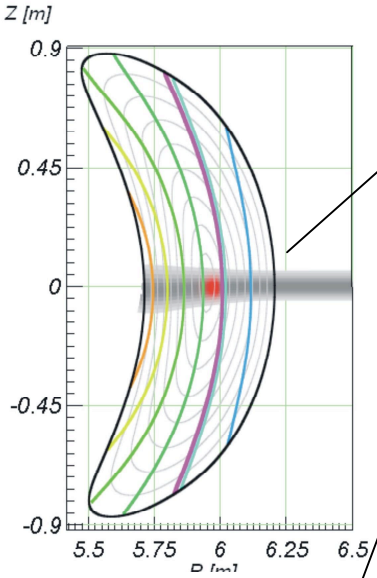
RAMI + Power-density vs. Optical quality

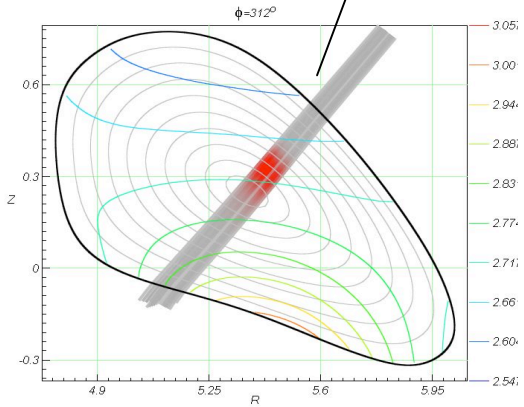
- Reduced steering range: toroidal < 20° , poloidal < 20 °
- Reduced focussing (smaller aperture)

- Remote Steering: 27 RF-beams per A-port (1 MW/beam)
- large gain in ECRH-power /Port area: 100 MW/m^{-2}
- large gain in RAMI

The W7X Launchers

Access from LFS (Front Steering) and HFS (Remote steering)

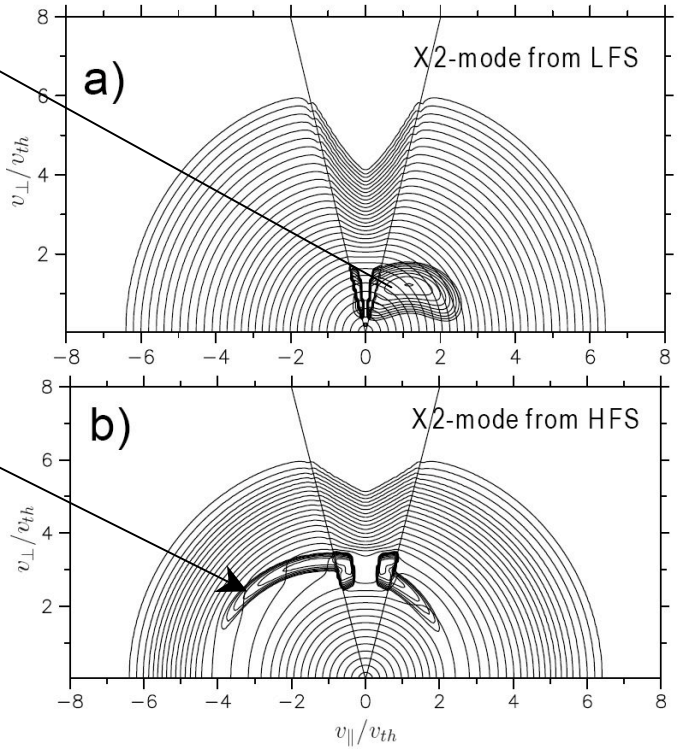




Standard launch from A/E-ports , 10 beams,
high magnetic field gradient,
strong localization,
coupling to thermal electrons

HFS- launch from N-ports , 2 beams,
low magnetic field gradient,
very sensitive to B and ß
preferred coupling to
suprathermal electrons

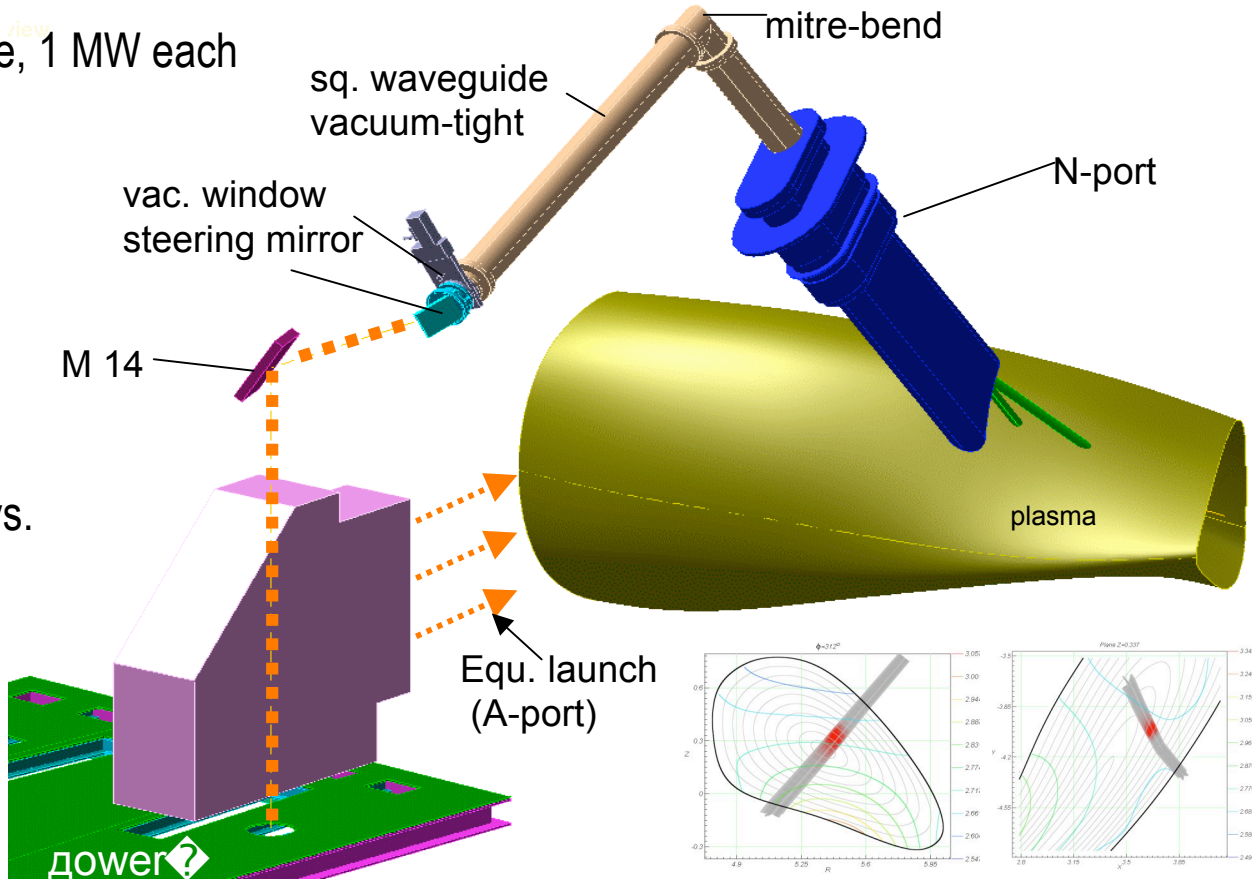
- confinement physics
- trapped vs. passing particles



The Remote Steering Launcher for W7-X

CW-High Field Side Launch (N-port)

- two narrow N-ports available, 1 MW each
- total length 5.1 m
- low magnetic field gradient
- absorption is preferably by suprathermal electrons
- confinement studies, comparison of bulk-heating vs. suprathermal heating
- phase space physics



W7-X and ECRH: Summary

- ECRH is the 'day one' CW heating system for W7-X, ITER, and, very likely, for DEMO as well
- The demands for high power, high flexibility and multi tasking must be satisfied while observing a high 'RAMI'-standard. Some present-day approaches must be reconsidered under RAMI-aspects
- A generic type 1.5 MW Gyrotron operating at 3 frequencies (e.g. 105/140/175 GHz) is proposed, which can satisfy the needs of many devices and applications
- tuneable, high power, CW, diplexers are robust and allow switching, distribution and combination of rf-beams during continuous gyrotron operation
- remote steering launchers are simple structures and can be improved with respect to steering range and transmission losses. They have no movable in-vessel parts and allow a high port-through power density (100 MW/m^{-2})