KIT Karlsruhe Institute of Technology | HELLAS | THALES | University of Stuttgart Germany | MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

The ECRH-Power Upgrade at the Wendelstein 7-X Stellarator

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Outline

- Motivation
- General strategy
- Gyrotrons
- Transmission line
- Gyrotron control

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Motivation: W7-X Future Operation Scenarios

Important to distinguish scenarios

(a) Reactor relevant power fluxes on plasma facing components in steady state.

long-pulse operation (10MW@1800s, 10MW/m^2 max. heat loads on PFC)

no upgrades of plasma facing components (PFC) necessary

ECRH scenario; existing 10 gyrotrons + 2 new 1.5 MW gyrotrons.

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(b) Reactor relevant plasma pressure and confinement

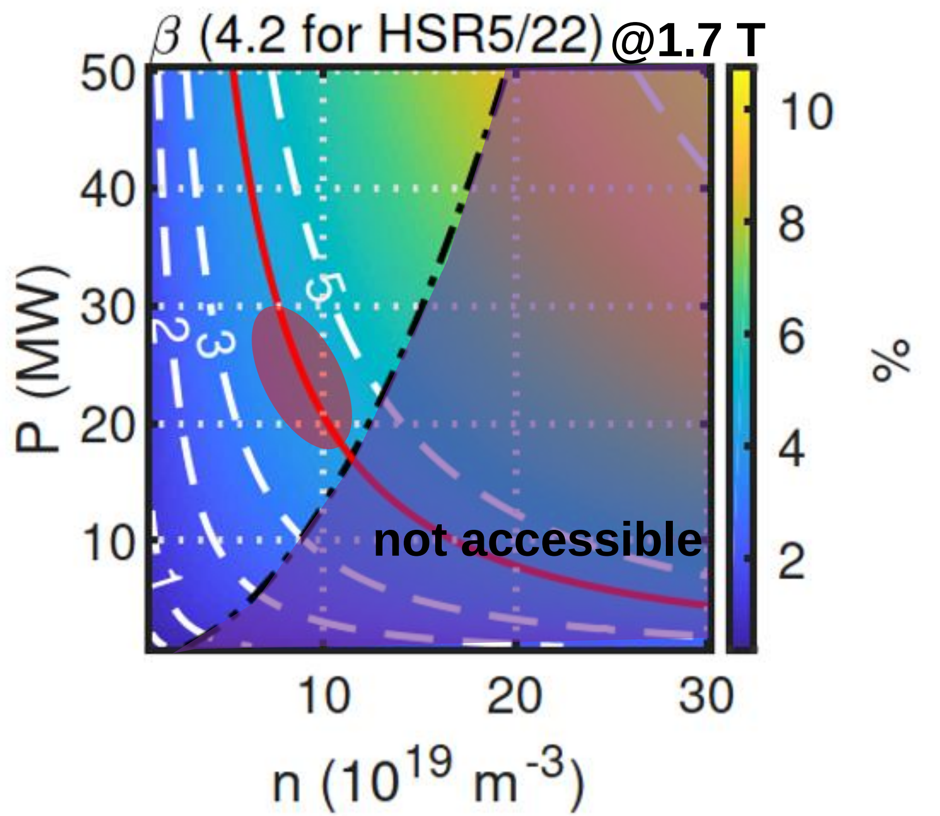
High-performance operation needs

4 x 1.5 MW + 4 x 2 MW additional gyrotrons + 4x1MW

existing gyrotrons for total power of 18 MW.

total heating power of P_{total}=20-30MW for a maximum discharge length of t_{pulse}**<10s** to be achieved by ECRH and NBI heating operation at **B=1.7T (X3 heating 140 GHz)** required for high-β operation.

courtesy of A. Alonso



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General Strategy: Lessons Learned

- Purchase of “serial gyrotrons” prohibits progress.

  The successful design is frozen for many years. => outdated gyrotrons

- Consider the whole ECRH-system.

  The gyrotron is the “motor”, but the ECRH system is the “car”.

  The weakest component determines the performance.

- Long pulse or cw operation requires a different interlock strategy than for pulsed operation.

  Online analysis of interlock events.

  Categorisation interlock signals.

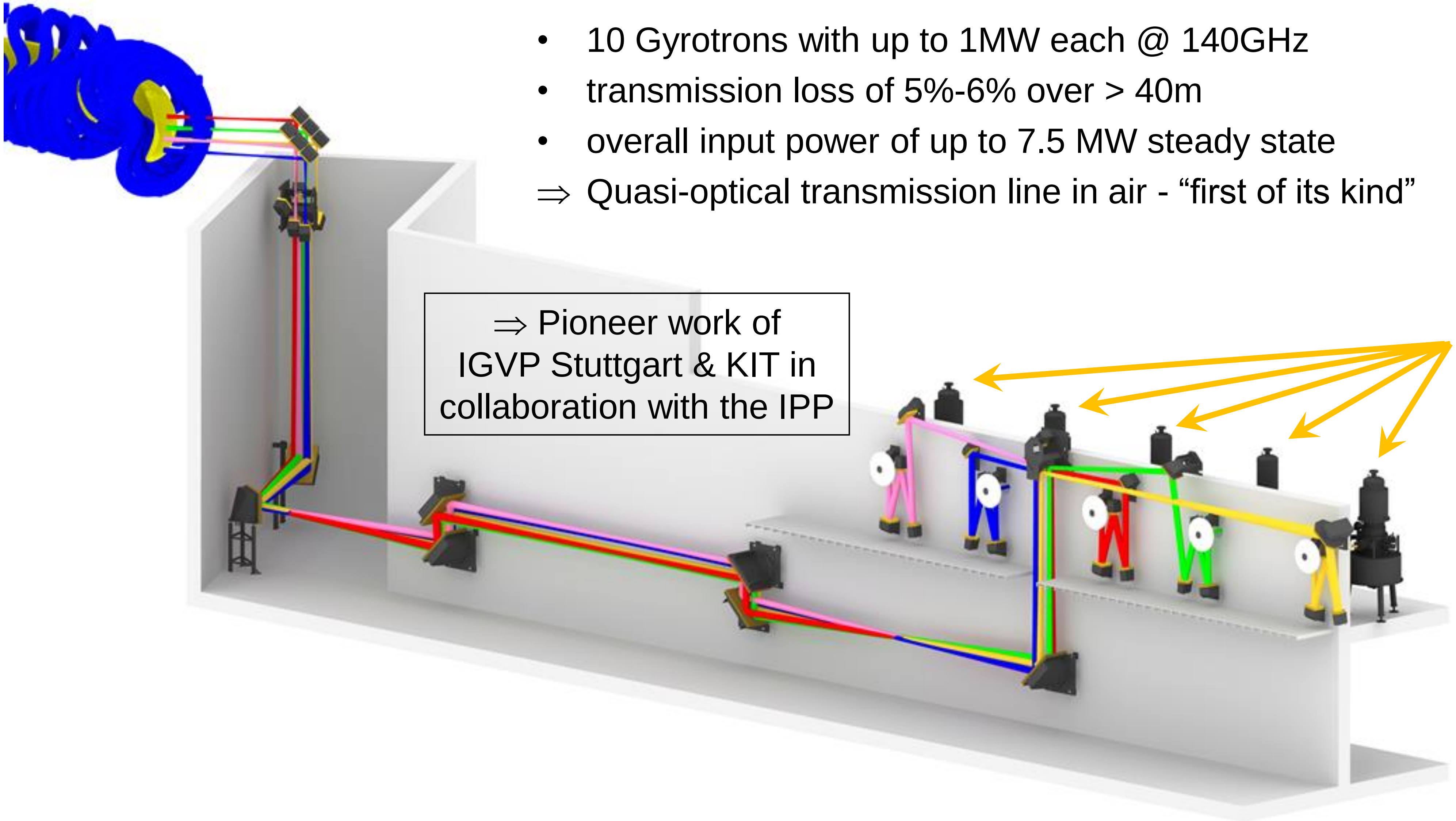
  Restart after interlock must be possible.

- Minimize complexity to increase reliability.

General Strategy: Upgrade of the installation

- 10 Gyrotrons with up to 1MW each @ 140GHz
- transmission loss of 5%-6% over > 40m
- overall input power of up to 7.5 MW steady state

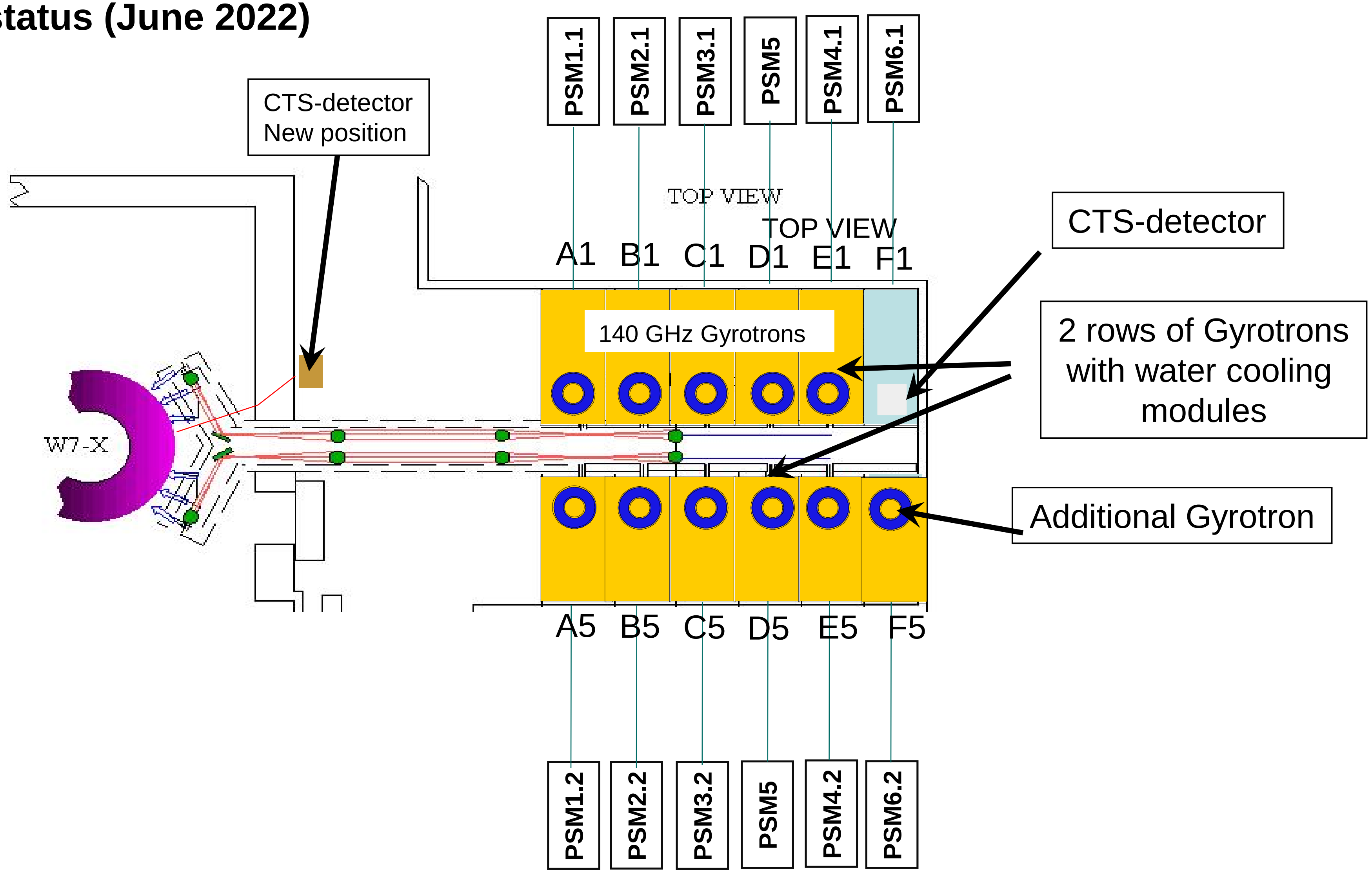
⇒ Quasi-optical transmission line in air - “first of its kind”



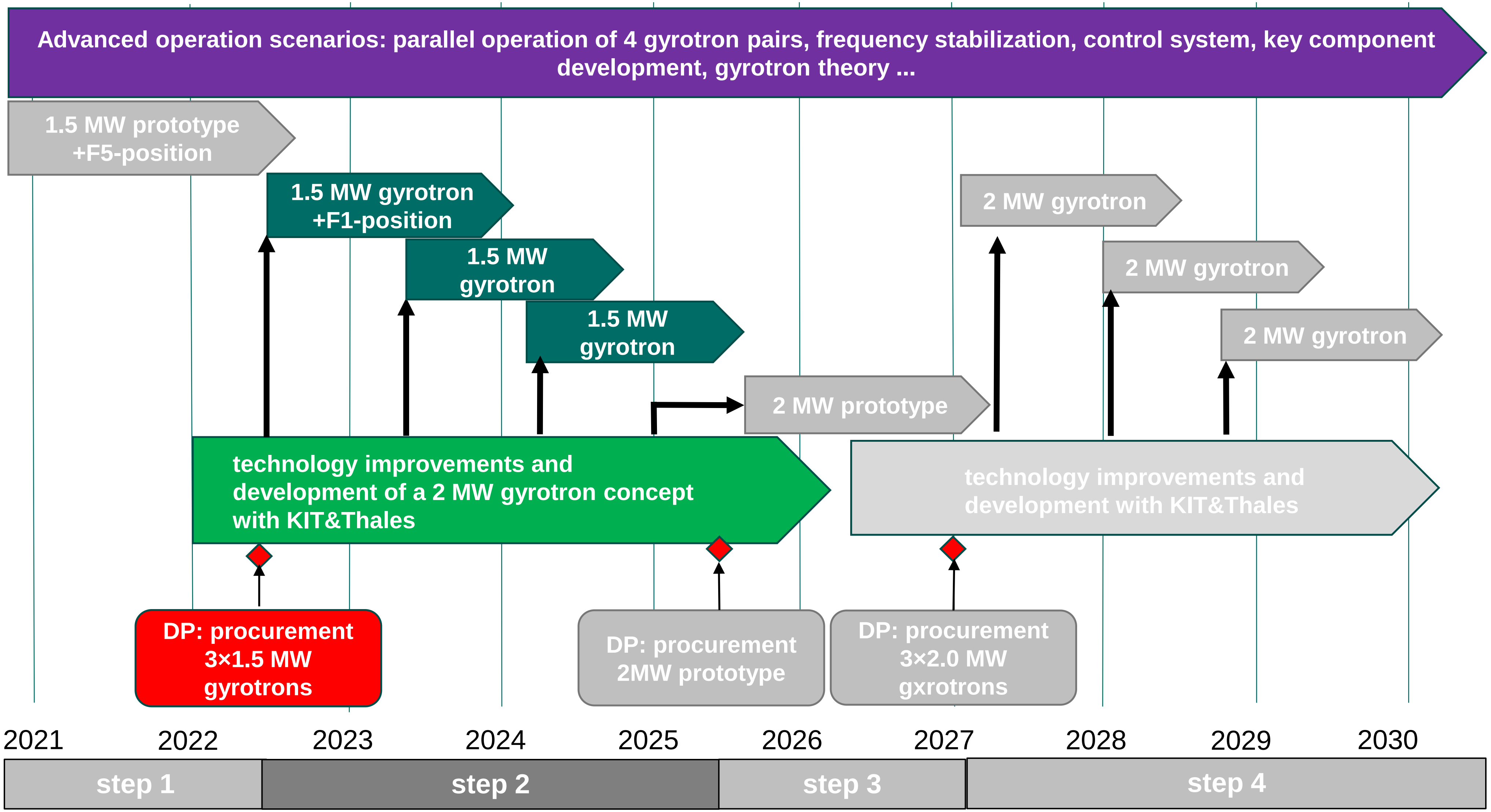
⇒ Pioneer work of IGVP Stuttgart & KIT in collaboration with the IPP

Upgrade of the ECRH Installation to 12 Gyrotron Positions

Actual status (June 2022)



Increase the Individual Gyrotron Power to 1.5 and 2 MW



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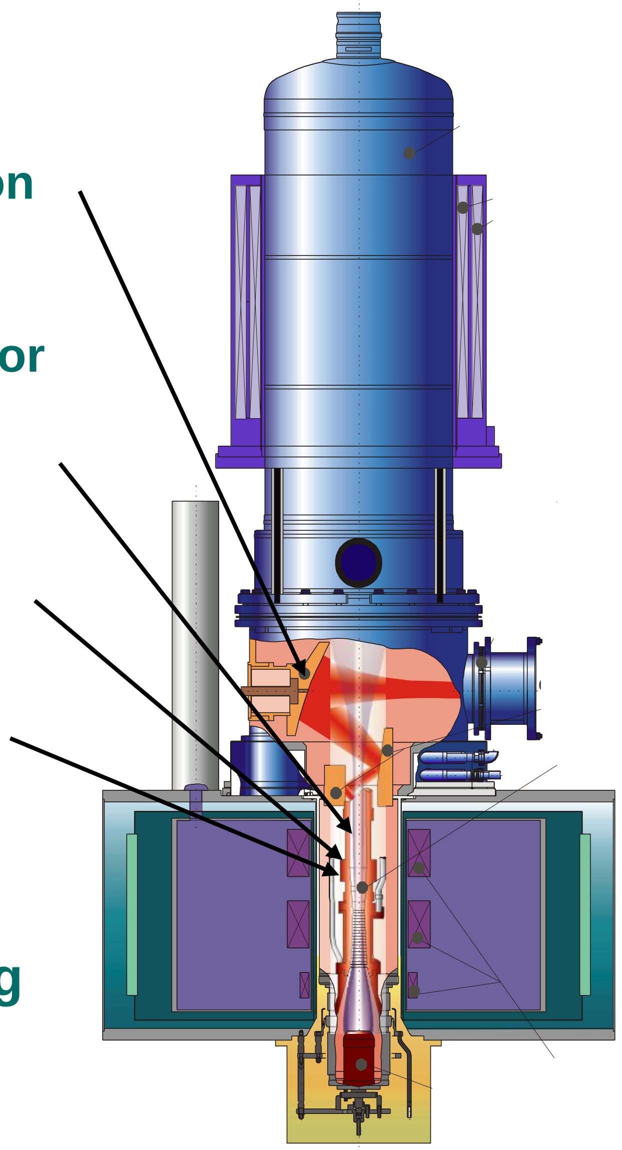
Gyrotron Design Improvements in collaboration with KIT and Thales

Step1 completed

- **Adjustable mirror to center beam on diamond disc.**
- **New hybrid type launcher and mirror design** (conversion efficiency enhancement 95%->98%)
- **Larger cavity (20.48-> 22.83)**
  TE28.08->TE28.10 operating mode
- **optimized cavity cooling**



New gyrotrons fit in the existing W7-X installation!

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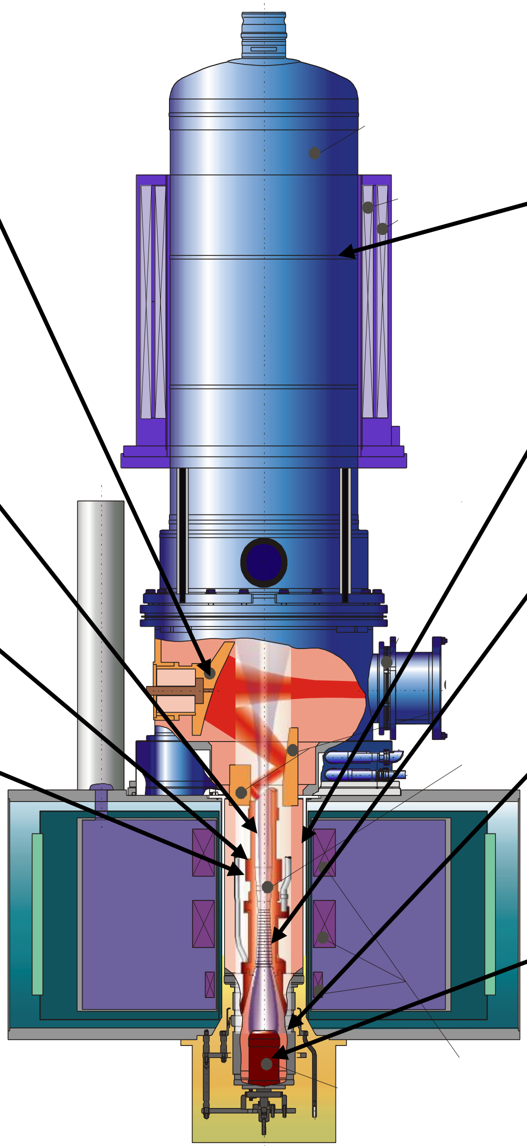

Step2 planed

- **Toughen up the collector for > 2 MW load.**
- **Enhance Cavity Cooling > 20 MW/m^2**
  Mini and micro channel cooling.
- **Simplify and optimize beam tunnel for 80 A**
- **Triode gyrotron operation**
  Insulate anode from body for ultra fast modulation (phase locking)
- **Toughen up the electron gun for 80 A**
  Potted cathode (no glowing filament)

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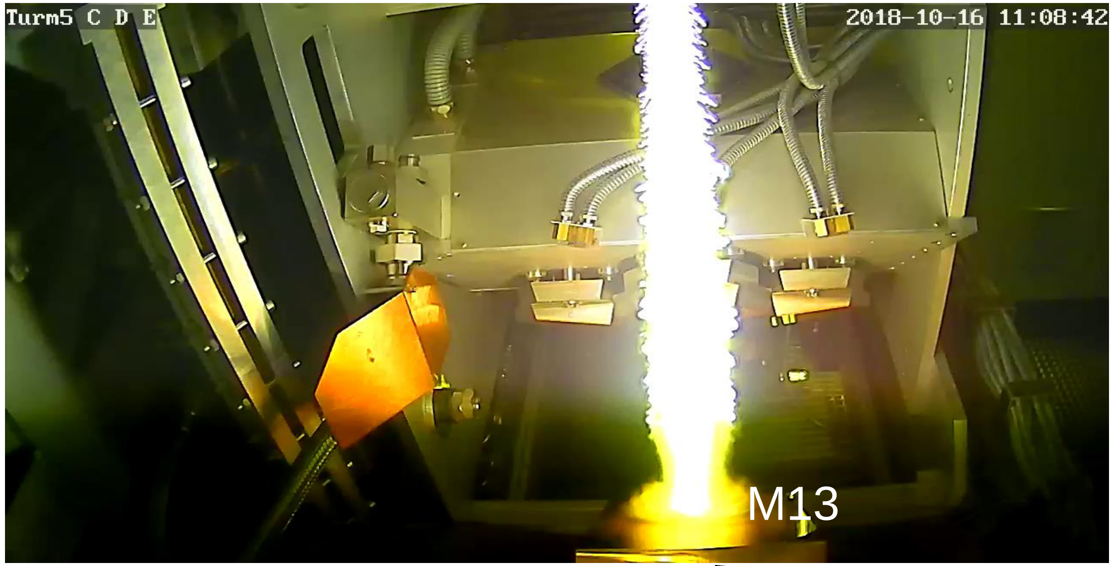
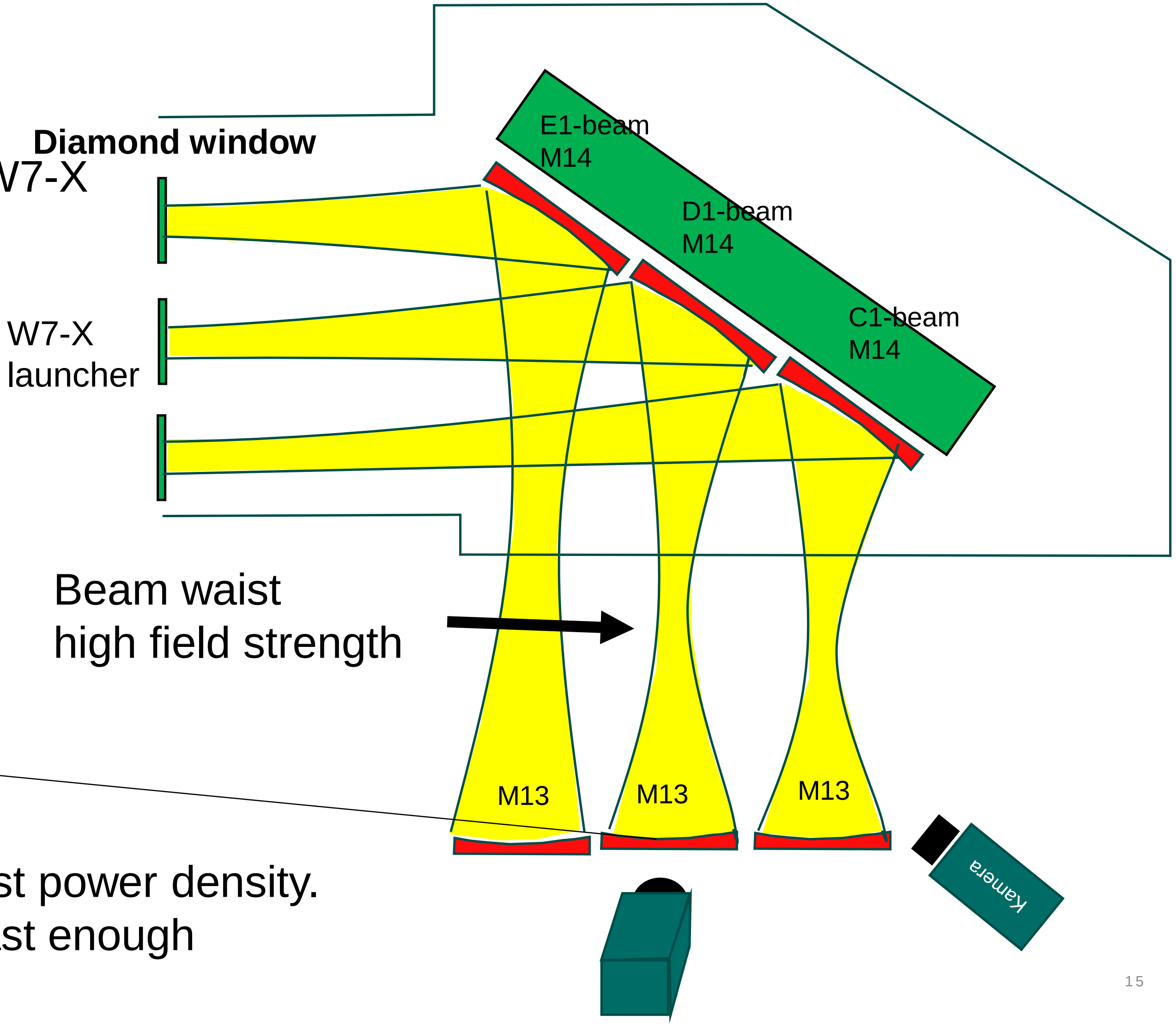
Transmission Line: Arcing Due to Humidity

Arc between M13 und M14 of D1-Beam (close to W7-X

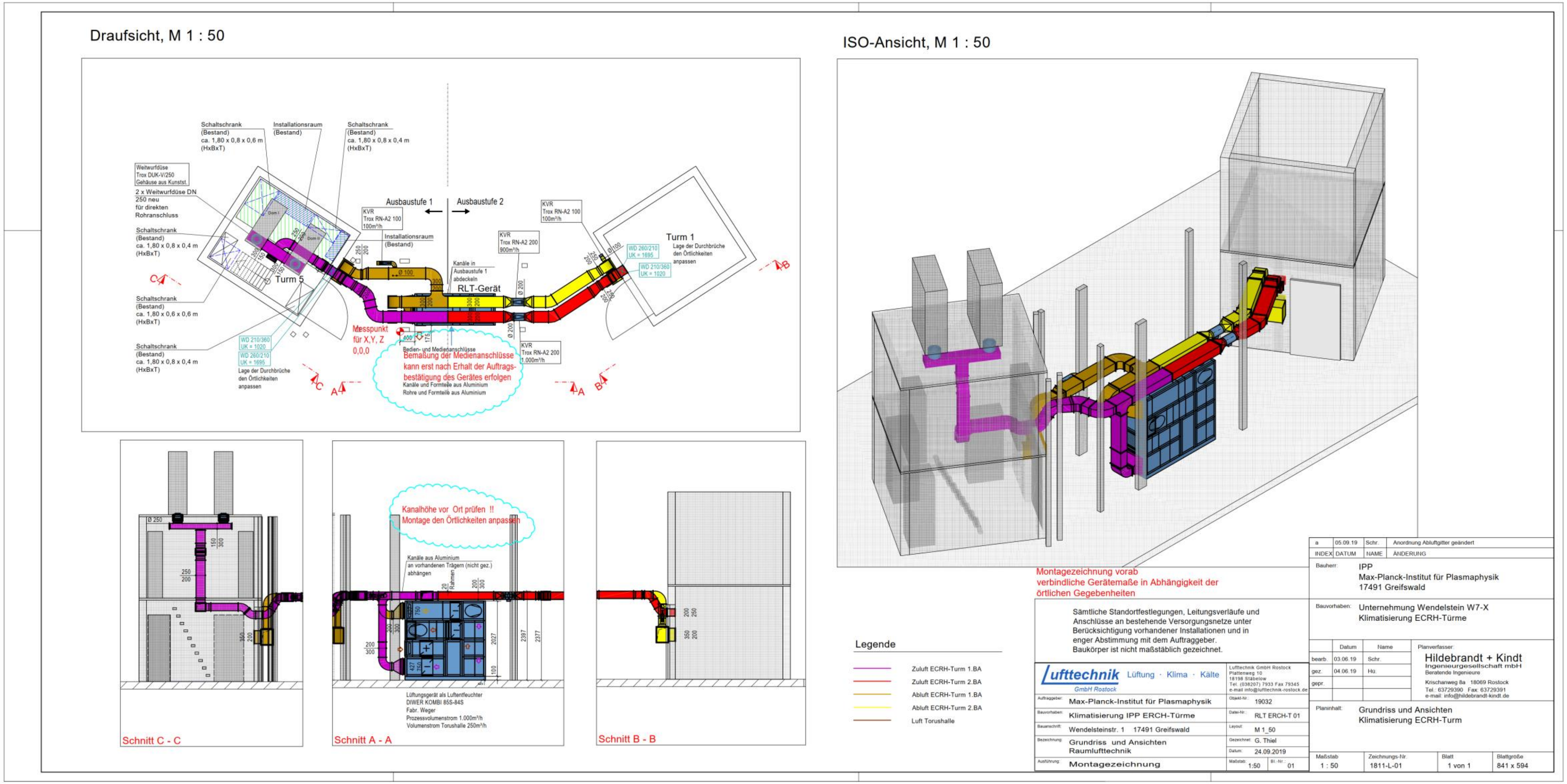




Lessons learned:

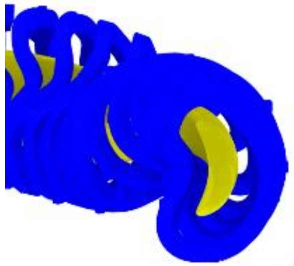
- Humidity causes arcing at the position of highest power density.
- Arc-detectors based on light emission are not fast enough
  to allow an immediate re-start.
- Change to arc-detection by RF-signals.

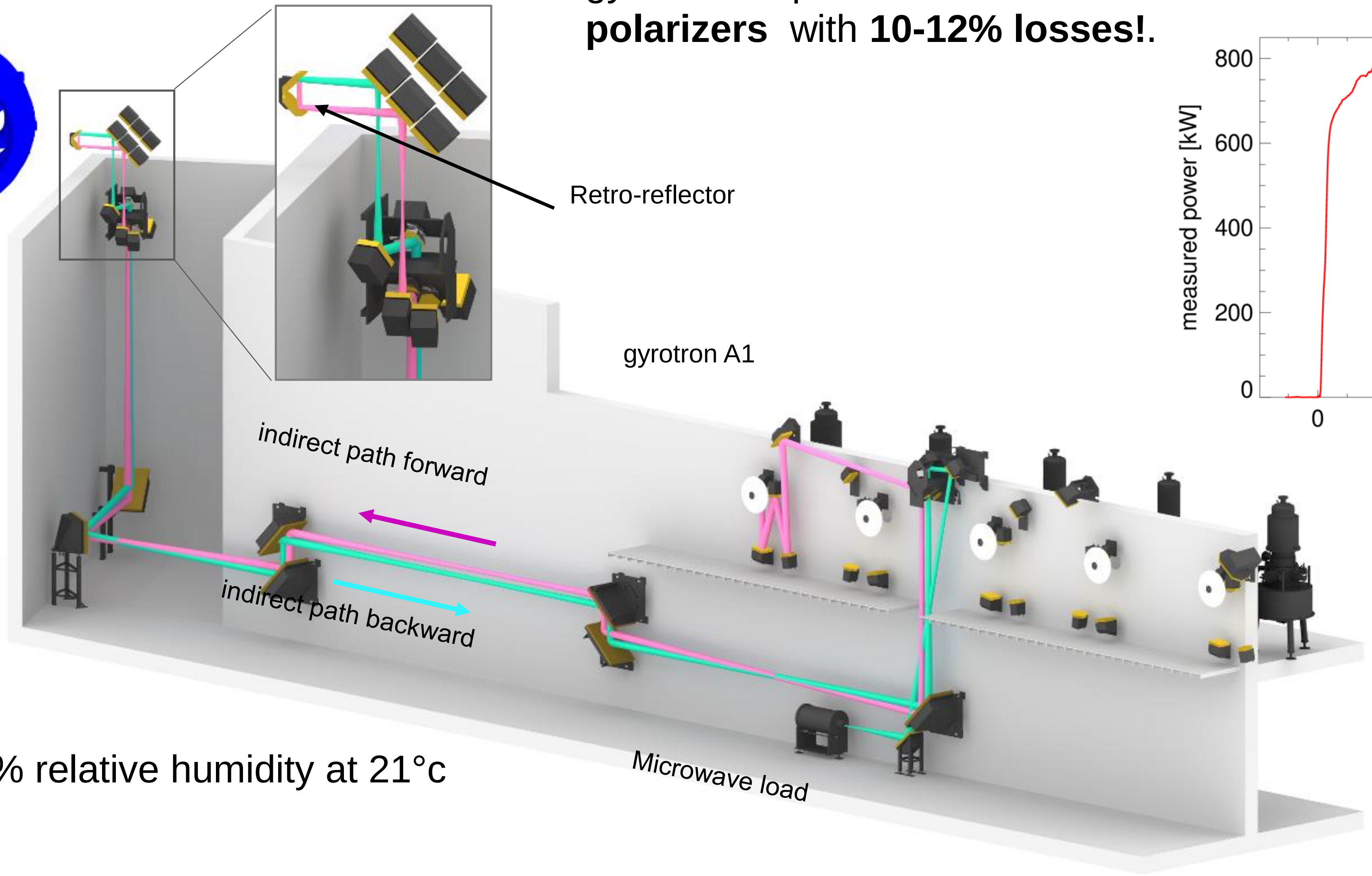
High Performance Air Drying System

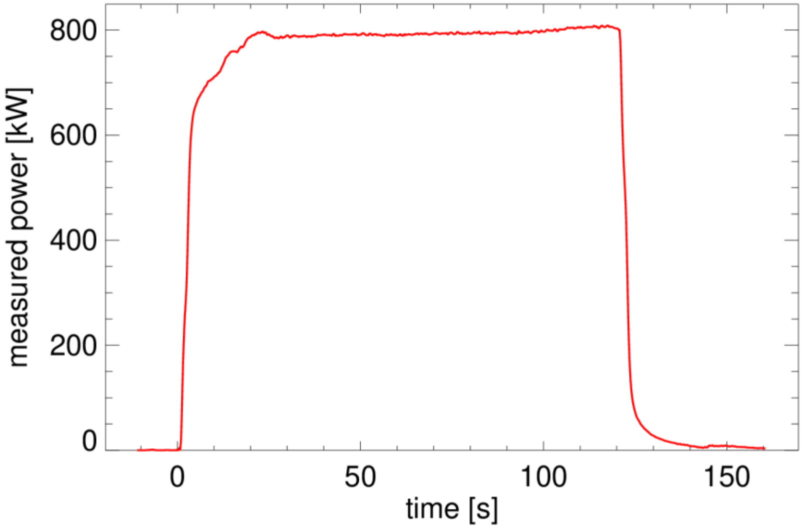


Transmission Line: Full Power Test

120 second operation at full gyrotron power with about **0.9 MW** at gyrotron output. Transmission over about **100 m** with **29 mirror+ 2 polarizers** with **10-12% losses!**.







<20 % relative humidity at 21°c

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Gyrotron Control: Operation Experience

Interlocks in OP1.2b

Interlock / Gyrotron	A1	B1	C1	D1	E1	A5	B5	C5	D5	E5	Summe
RF (mode loss)	20	10	12	23	5	2	1	2	3	10	88
I-Body	5	5	8	9	14	6	3	2	1	16	69
Overcurrent	4	0	17	5	8	1	5	0	5	2	47
Arc Gyrotron	1	8	0	0	0	3	0	0	0	0	12
Arc M13 (ECRH tower)	20	6	16	21	17	13	12	15	27	21	168
Sweep PSU	6	9	1	1	1	7	2	0	0	3	30
Cooling	0	2	0	0	4	4	8	1	4	4	27
Communication	3	1	3	2	8	0	3	0	1	1	22
Summe	59	41	57	61	57	36	34	20	41	57	

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Boosting control of emitter heater

air condition, new optics and fast arc detection based on RF-measurement

modernisation and simplification

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Fast control system improvement

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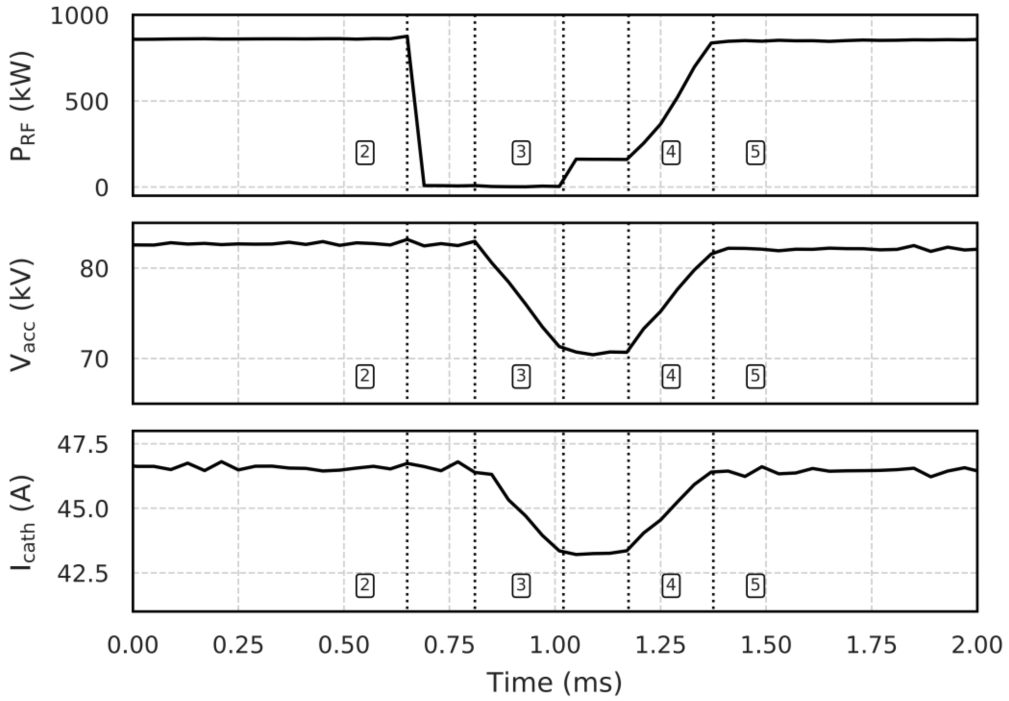
New Strategy: allow restart of gyrotron whenever possible.

Gyrotron Control: Restarting Gyrotron Operation

Mode recovery system

PhD F. Wilde



1) Mode loss detection
2) Ramp down voltage
3) Mode is re-excited
4) Ramp voltage sligtly below set value
5) Slow voltage ramp towards set value

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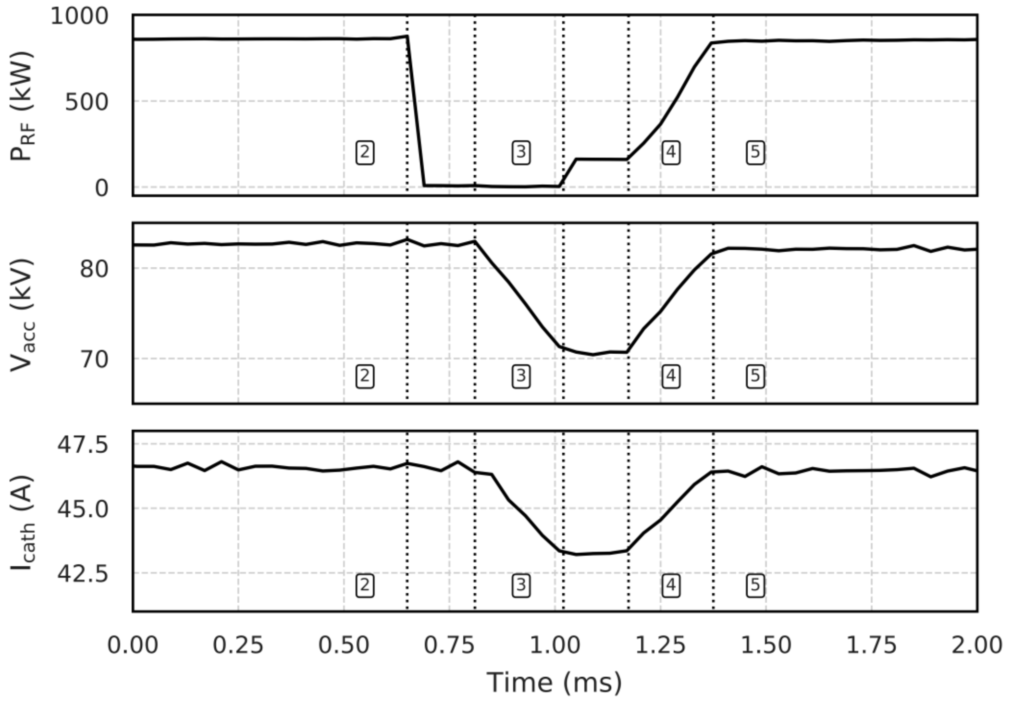
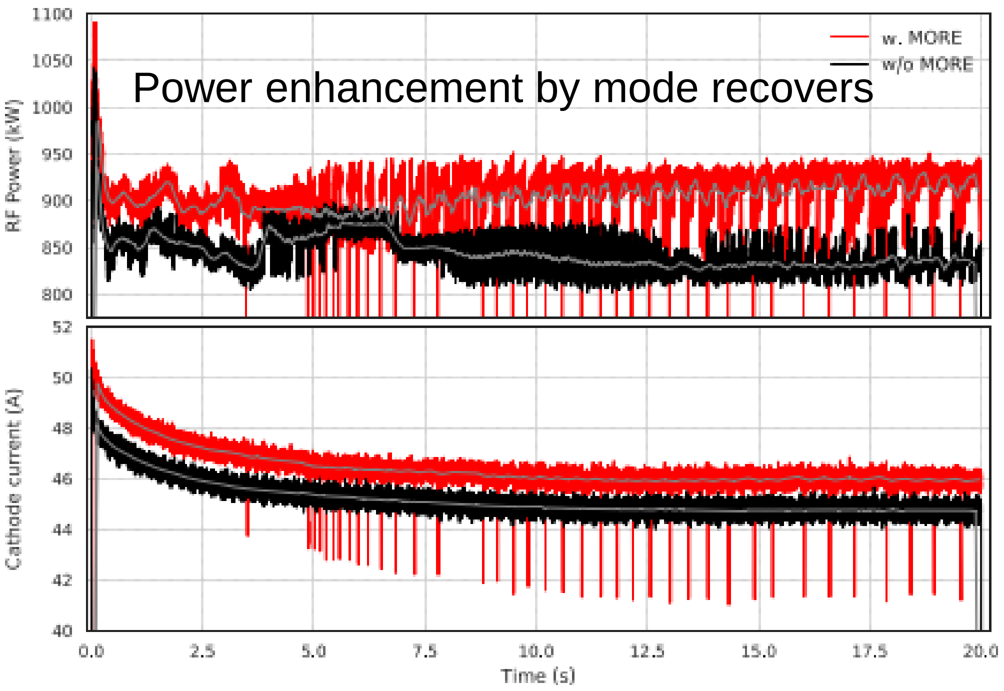
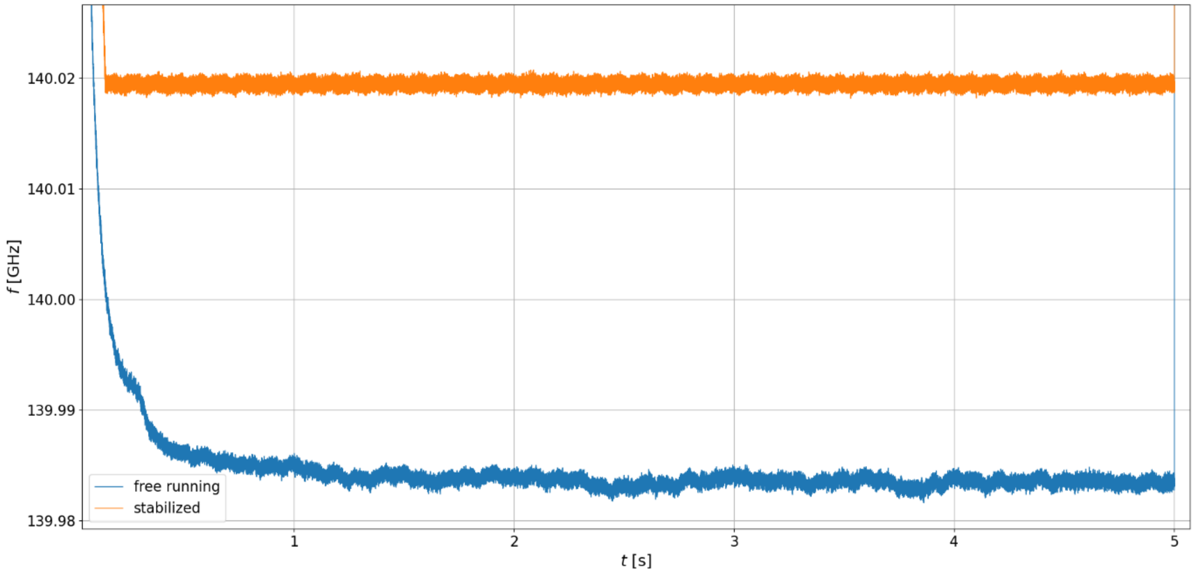


Power enhancement by mode recovers



Gyrotron Control: Frequency and (Phase Stabilisation)

Frequency stabilisation by PLL
L. Krier



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- Beat wave experiments with ECRH

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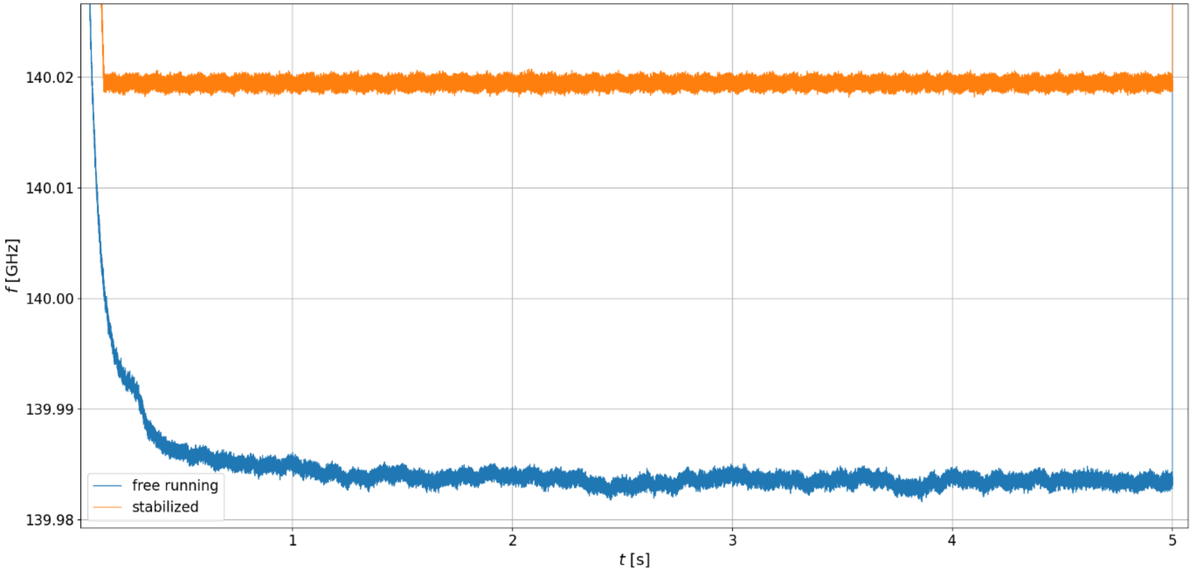

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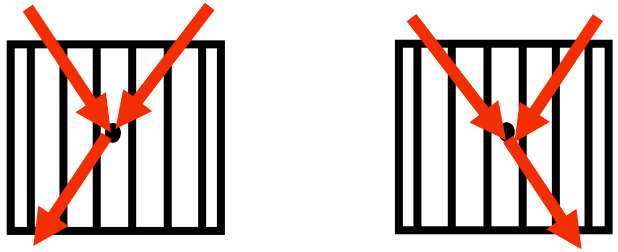
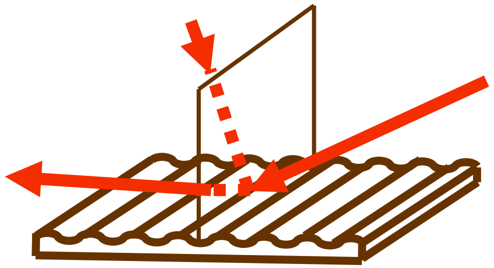
Complete phase locking will:

- Revolutionize the ECRH design (beam combining)
- Make new gyrotron applications possible (accelerator).

Magic Y: combining and switching by phase shift
M.Petelin IVEC 2014



$\varphi_1 - \varphi_2 = \pi/2$ $\varphi_2 - \varphi_1 = \pi/2$



Summary

- **Stepwise enhancement of the W7-X ECRH-system.**

  18 MW ECRH power at W7-X is envisaged for 2030.

- **Step by step gyrotron development that also strengthens the European gyrotron program with a view to ITER and other fusion facilities.**

- **Adequate upgrades of transmission line and control system.**

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Ultimate Goal:

phase controlled gyrotrons with 2MW unit power in 2030.