Theo Verdier, S. B. Korsholm, J. Rasmussen

Continuous Ultrafast Sampling for CTS: Implementation and Consequences for ITER Calibration

Overview

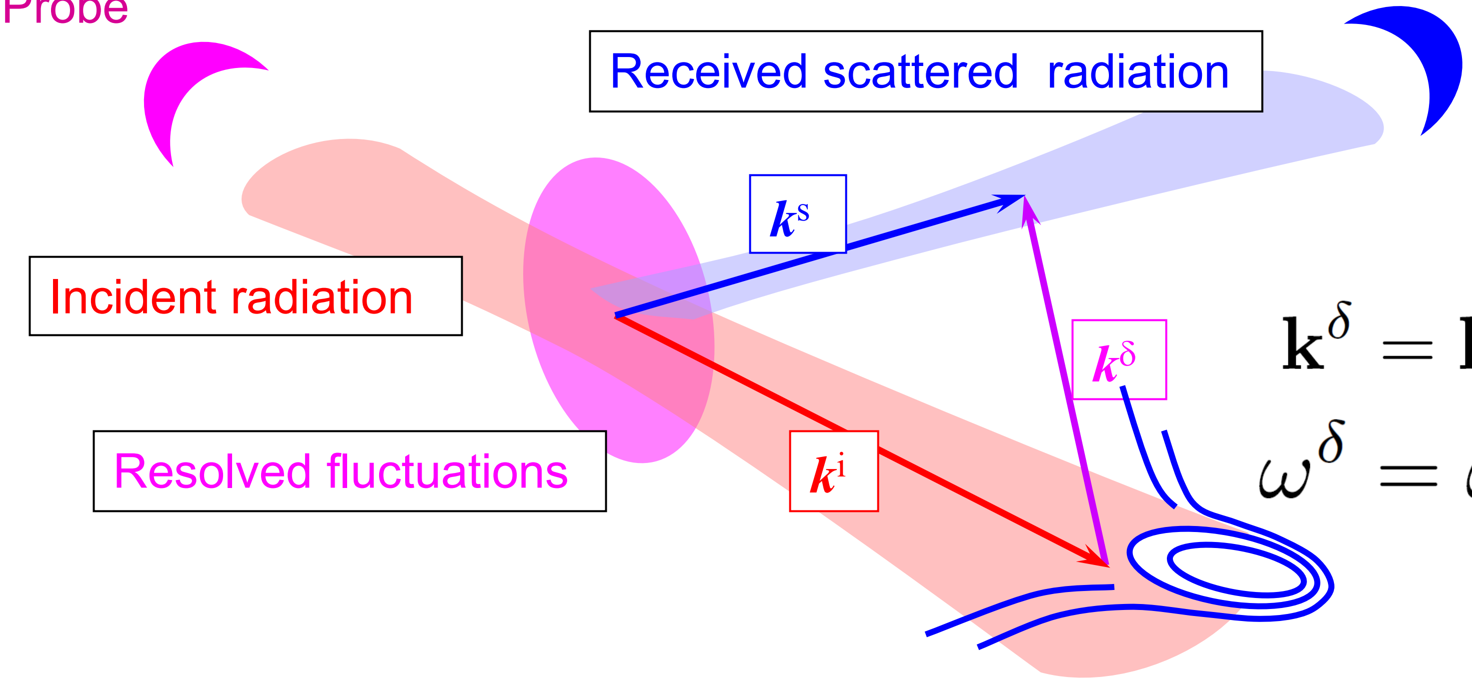
1. Collective Thomson Scattering
2. FPGA-based continuous ultrafast digitizer
3. ITER CTS
4. Dedicated calibration system
5. Calibration Procedure and Caveats

1. CTS

Collective Thomson Scattering principle

~1 MW in

Signal of interest
~1 nW out

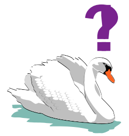


$$\mathbf{k}^{\delta} = \mathbf{k}^{\mathrm{s}} - \mathbf{k}^{\mathrm{i}}$$

$$\omega^{\delta} = \omega^{\mathrm{s}} - \omega^{\mathrm{i}}$$

Collective Thomson scattering resolves the 1D projected velocity distribution along $\boldsymbol{k}^{\delta}$:

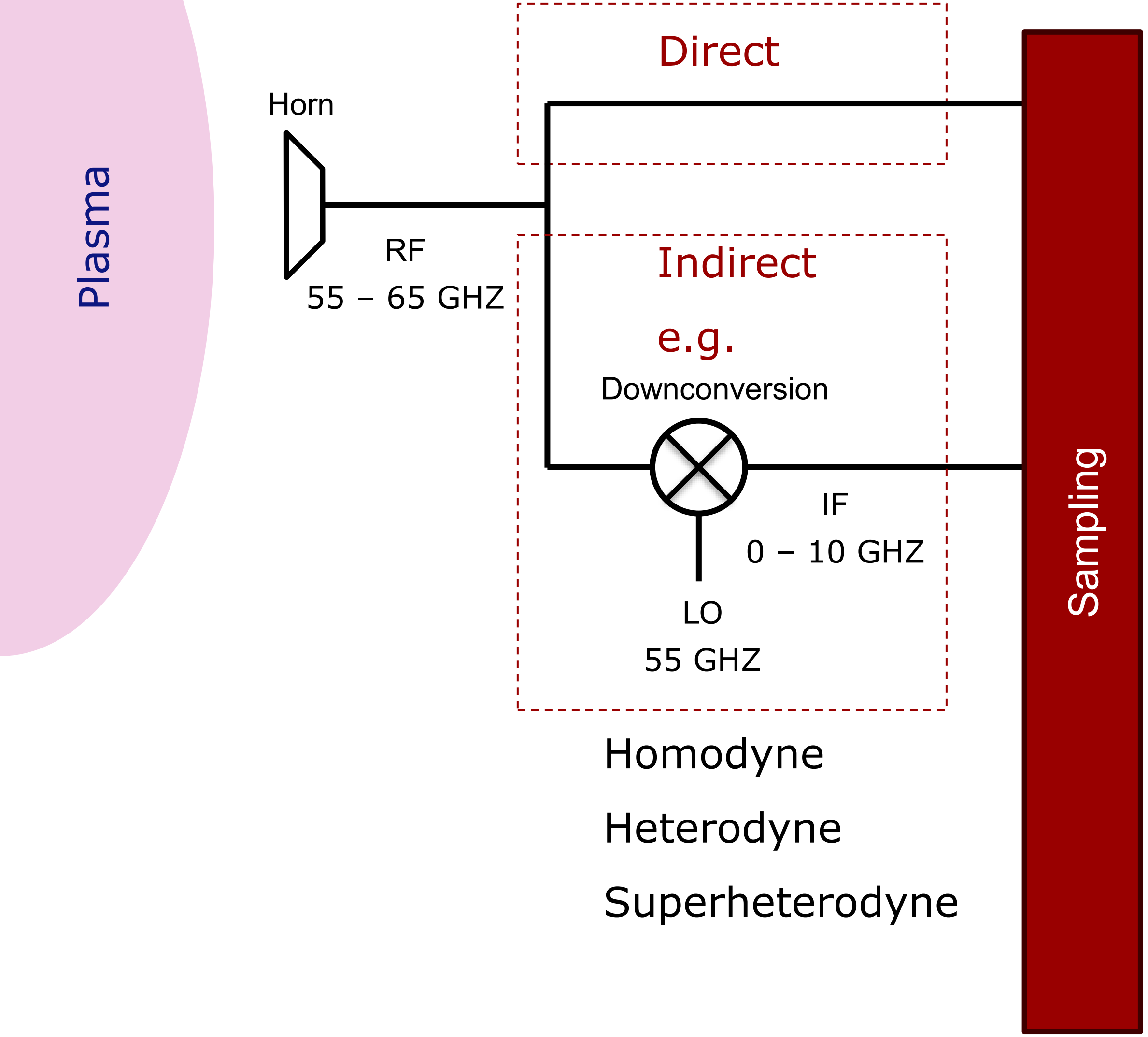
$$f^{(1)}(u) = \int \delta\left(u - \hat{\mathbf{k}}^{\delta} \cdot \mathbf{v}\right) f(\mathbf{v})\, d\mathbf{v}$$



$\leftarrow \lambda_{\mathrm{D}} \rightarrow$

2. FPGA-based continuous ultrafast digitizer

Direct sampling vs indirect



Homodyne

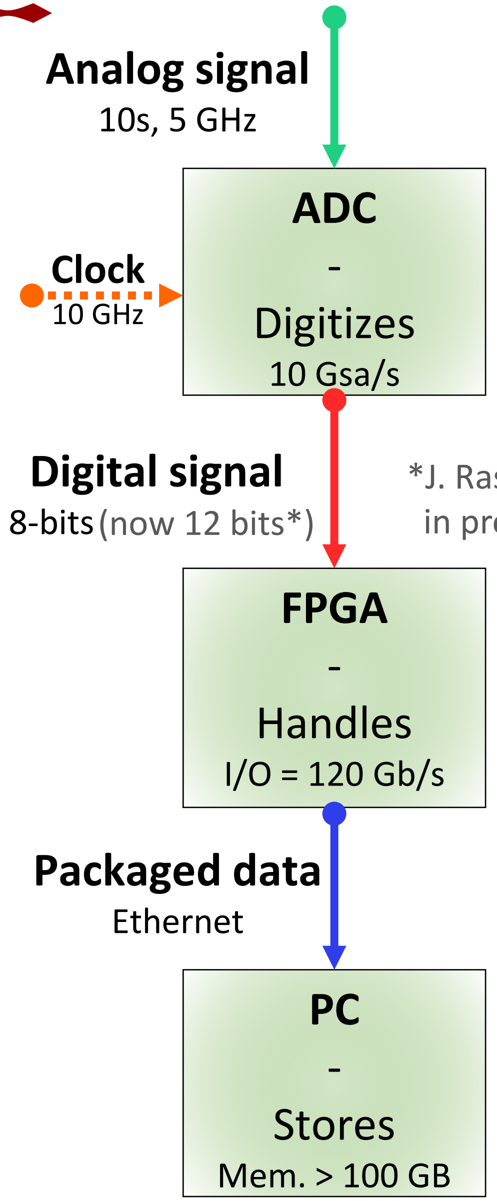
Heterodyne

Superheterodyne

	Filter Banks	RF Digitizers
Direct	**Pros:** CW, hardware bins **Cons:** Filters, electronics 10-100 MHz wide at 60 GHz Difficult/expensive Emergent solutions?	Requires 130 GS/s ➔ Non commercial ➔ CW Impossible 110 GS/s wasted
Indirect	**Pros:** Already done. Hardware bins, high resolution CW. **Cons:** Many potential electronic failures, frequency resolution per cost	**Pros:** Already done. Flexible time/frequency resolution. **Cons:** Lower resolution. Challenging data-rate. Multiple downconvesion

FPGA-based fast-digitizers

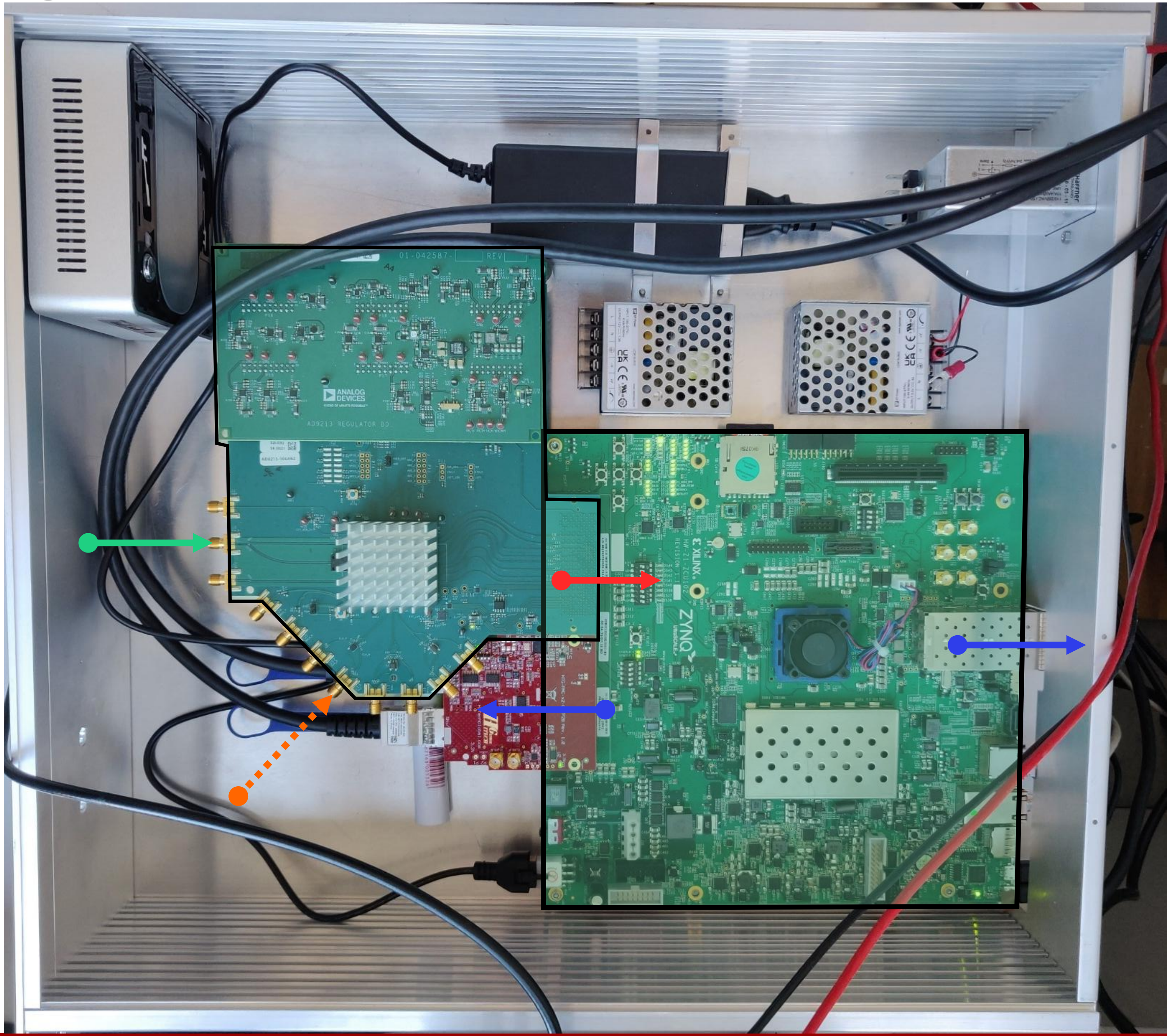
T. Verdier et al, Fus. Eng. Des. **206** (2024)



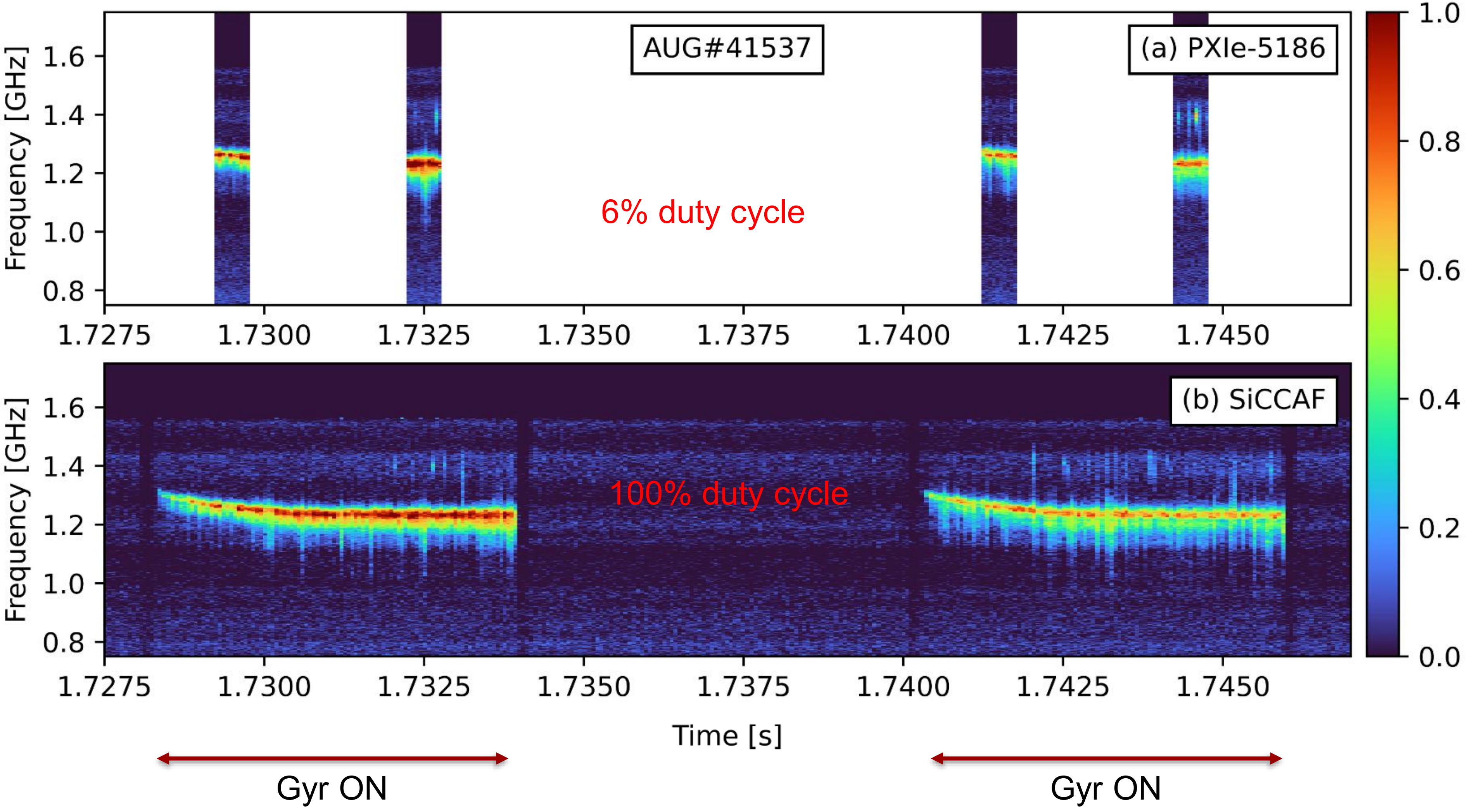
*J. Rasmussen et al, 2026, *JINST*,
in prep (EUROfus. pinboard #40728)

ADC:
Analog-to-digital
converter

FPGA:
Field-programmable
gate-array



Some measurements



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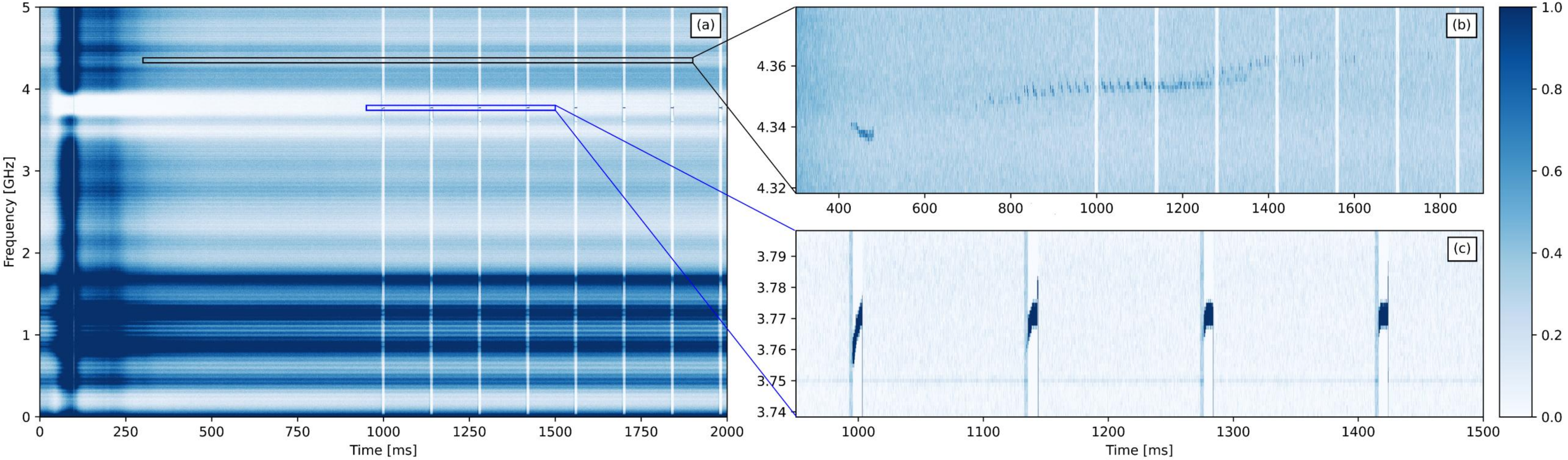
Wendelstein 7-X shot 20230330.23



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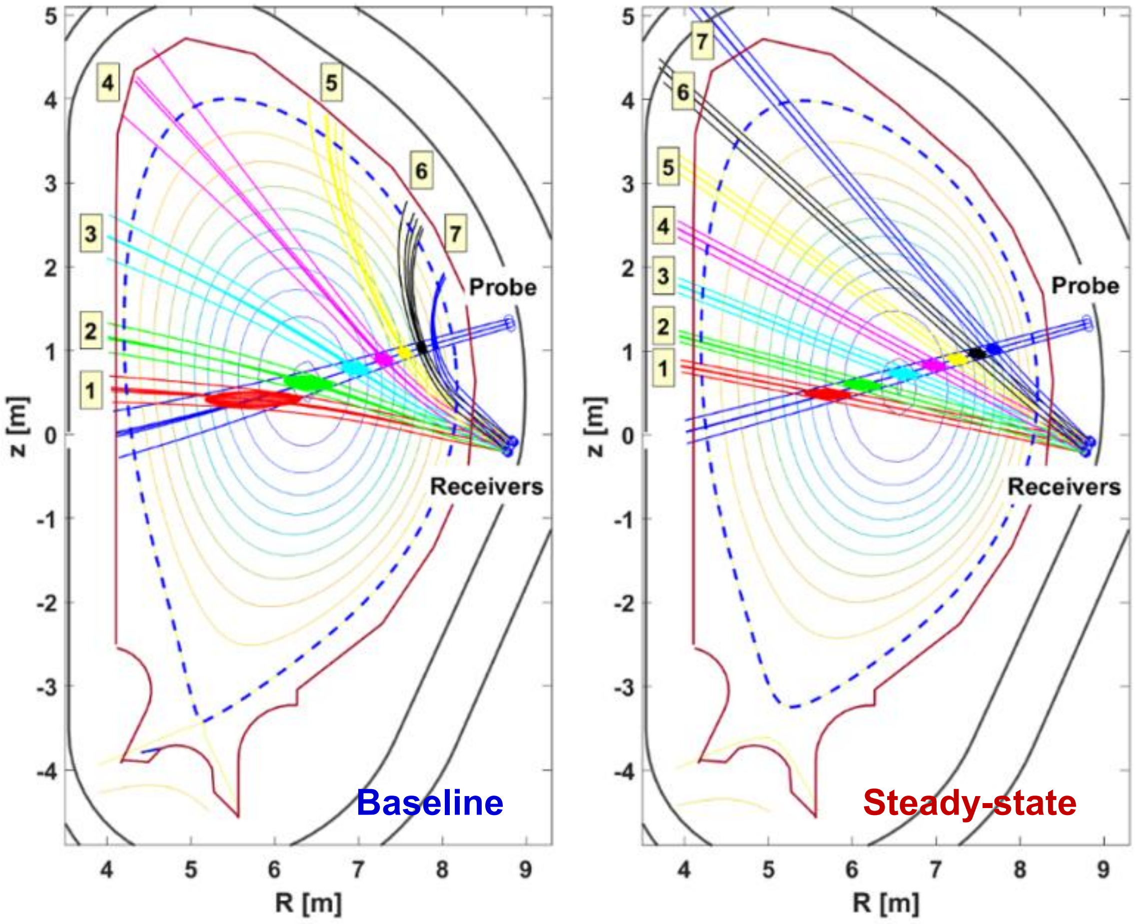
3. ITER CTS

ITER CTS purpose and setup



Measurement parameter	Range
*Alpha density profile	> 10^{17} m^{-3}
Alpha energy spectrum	0.3 – 3.5 MeV
*p, D, T, ^{3}He energy spectrum	0.1 – 1 MeV

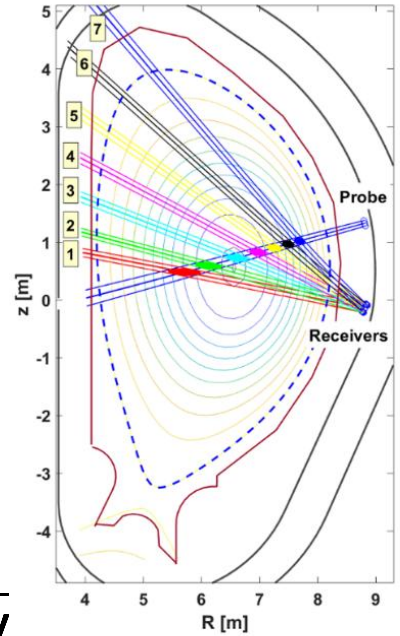
* Only CTS

Time res.	Spatial res.	Required Accuracy
100 ms	10–100 cm (50 cm in the center)	20%

7 Views + 1 Passive

DTU

Measurement performance

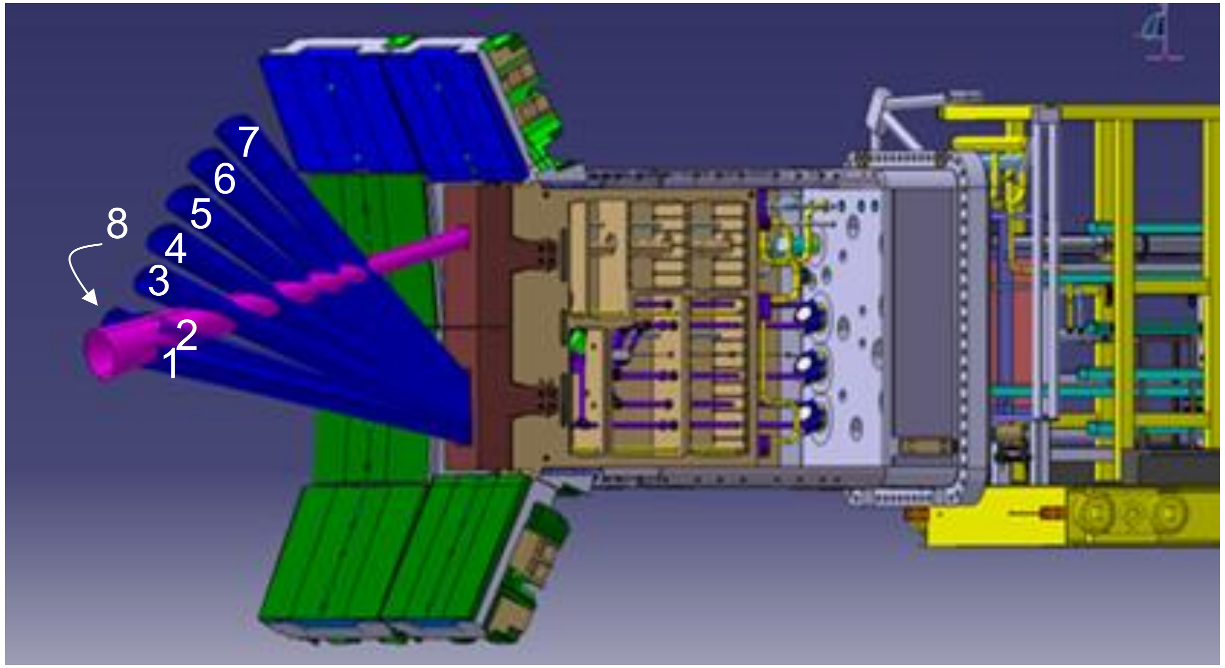


Measurement accuracy, based on trial fits to synthetic ITER CTS spectra:

	Measurement parameter	Range	Time res	Req acc	Inferred accuracy
MP068:	Alpha density profile at $n_\alpha > 10^{17}$ m^{-3}	-	100 ms	**20%**	**9** ± **2%** (*baseline* P_b=100 eV)
					8 ± **2%** (*steady-state*, P_b=1 keV)
MP069:	Alpha energy spectrum	E = 0.3-3.5 MeV	100 ms	**20%**	Spectral shape assumed in all inversions
MP070:	p, D, T, ^{3}He energy spectrum	E = 0.1–1 MeV	100 ms	**20%**	**3%** (*baseline*, integrated *g*(*u*) of fast D, P_b=100 eV))
					17% (*steady-state*, integrated *g*(*u*) of fast D, P_b=1 keV)

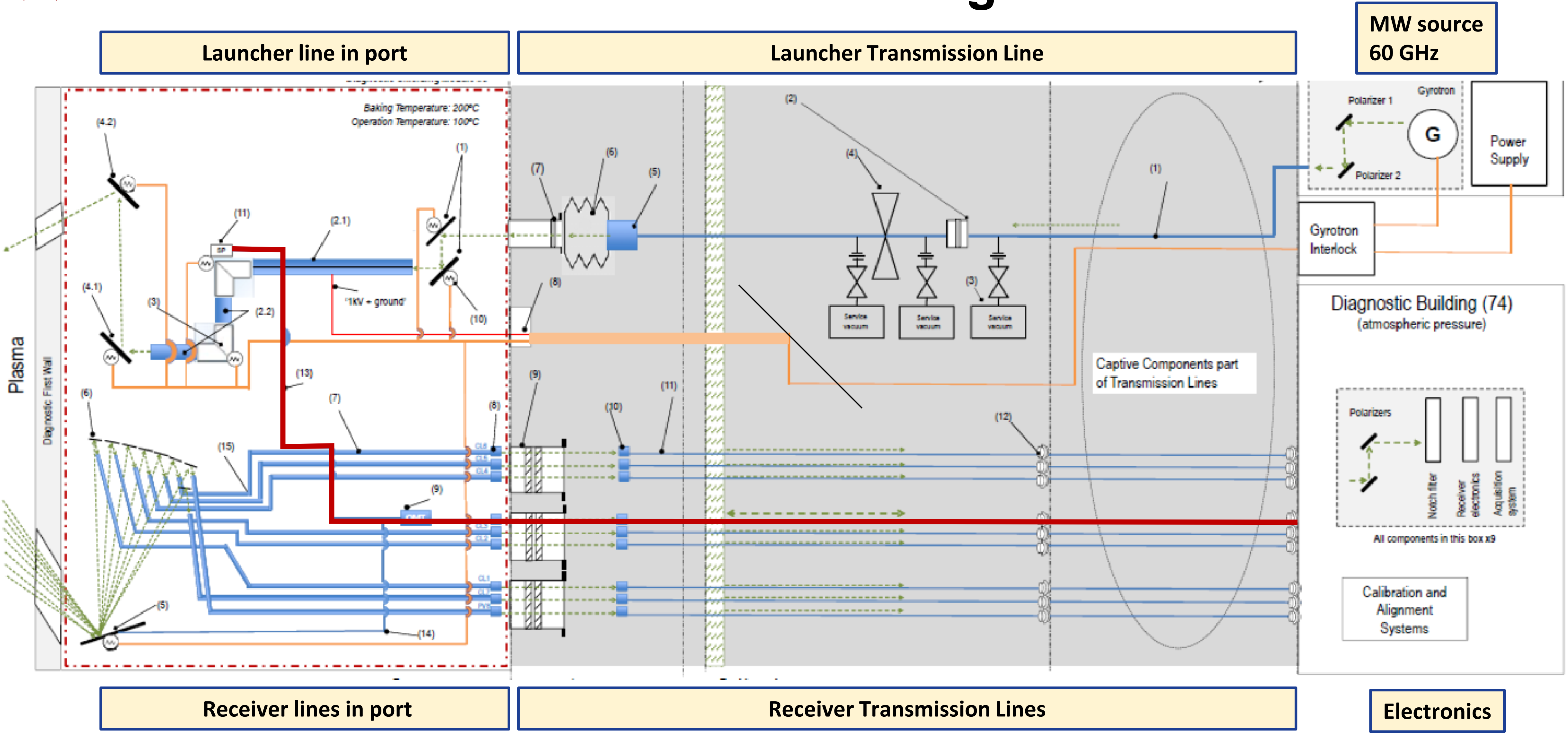
❖ J. Rasmussen et al., Nucl. Fusion **59**, 096051 (2019)
❖ J. Rasmussen et al., PPCF **61**, 095002 (2019)

Constituents of the ITER CTS diagnostic



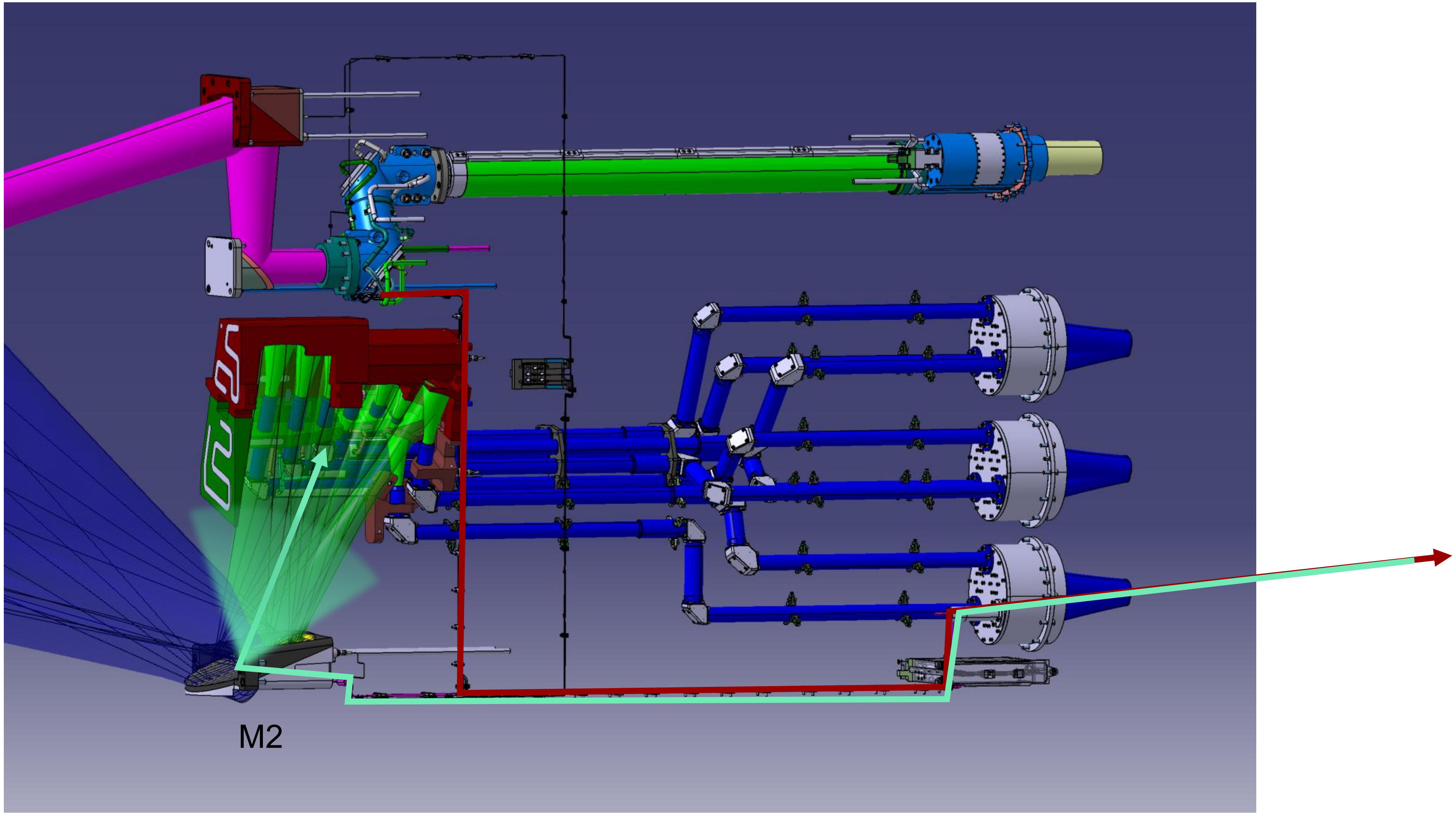
- Gyrotron (60 GHz, ~1.3 MW), power supply, and high power transmission line (from assembly hall)
- Port-plug based quasi-optical transmitter and receiver system
- Quasi-optical transmission lines from port-plug to diagnostic hall (~50 m)
- Receiver electronics (nW) and data acquisition (G samples s^{-1})

Schematic of the ITER CTS diagnostic



4. Dedicated calibration system

Highlight on calibration system

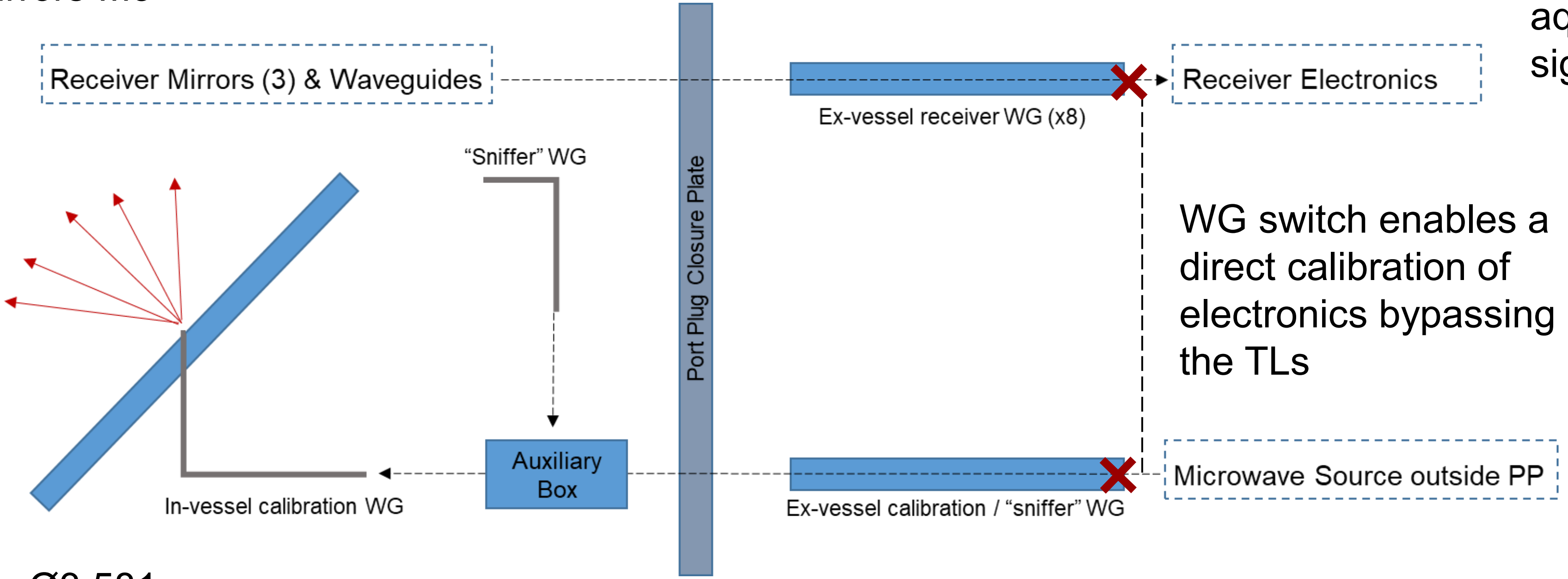


Principal functionality of calibration system

Signal picked up by individual secondary receiver mirrors M3

… and transmitted via the receiver TLs

Microwave receivers aquiring ”known” calibration signal;



WG switch enables a direct calibration of electronics bypassing the TLs

Emitting via Ø3.581 mm hole in center of plasma facing mirror M2

Transmission via 9^{th} receiver TL – the auxiliary TL

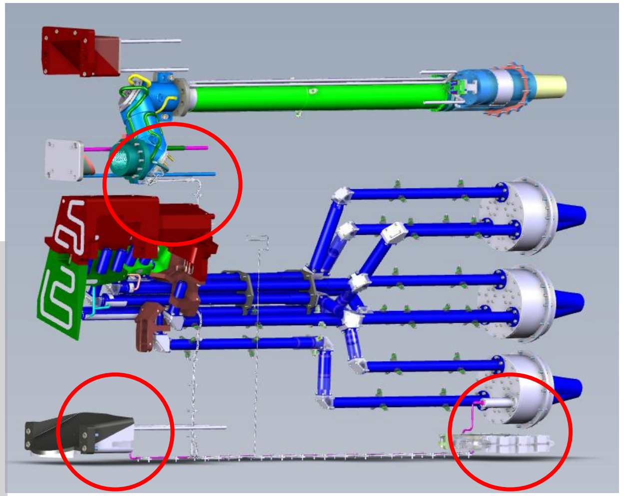
<1 W tunable (55-65 GHz) microwave source in diagnostic cubicle

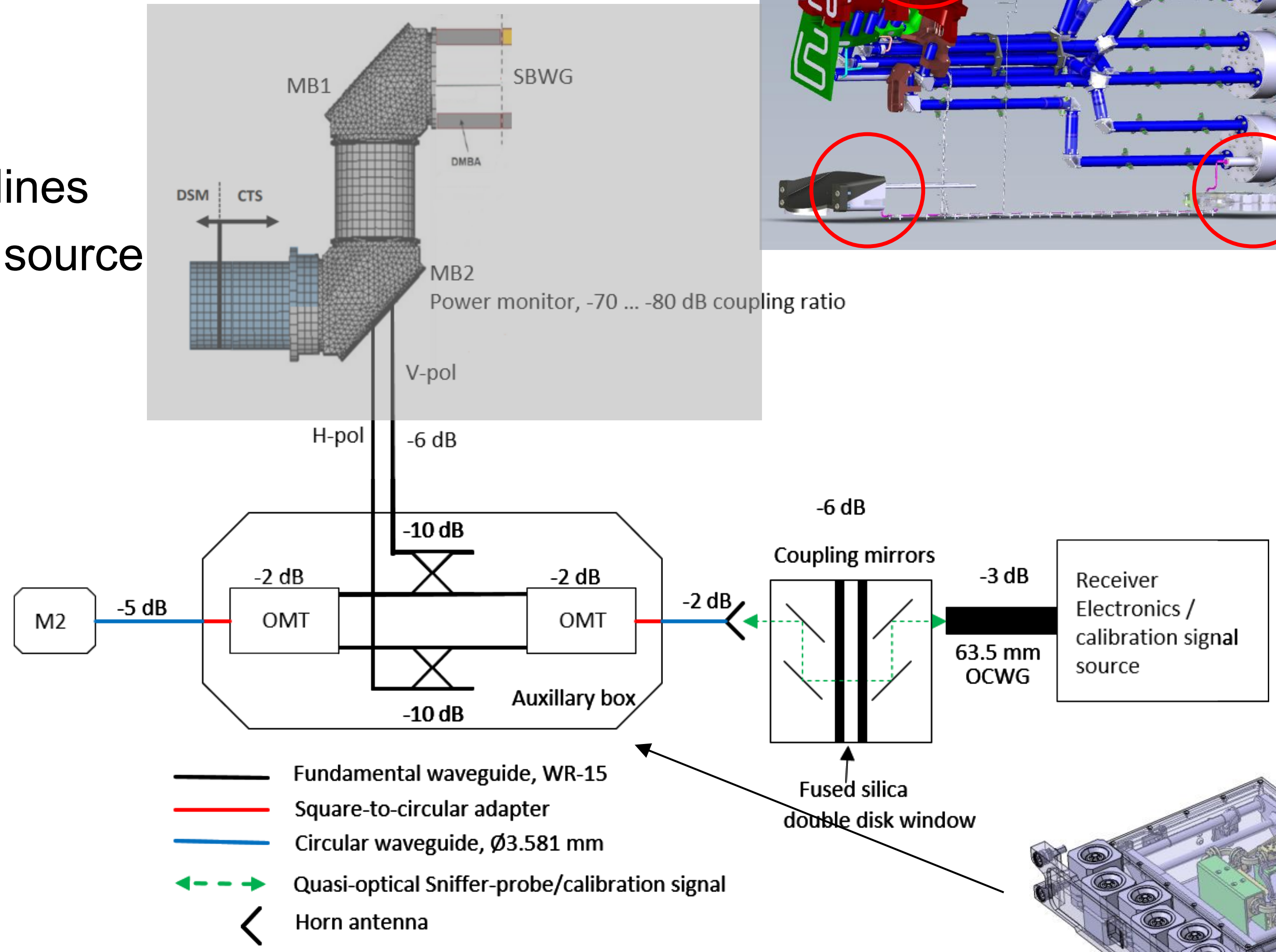
Calibration and alignment monitoring

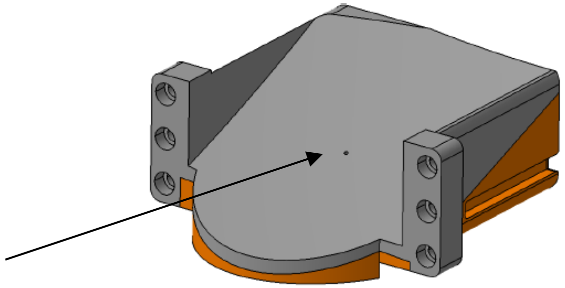
- Auxiliary system for
  - Sniffer probe for gyrotron probe beam
  - Calibration (in-situ) of receiver transmission lines
- Using only 1 transmission line and an external source

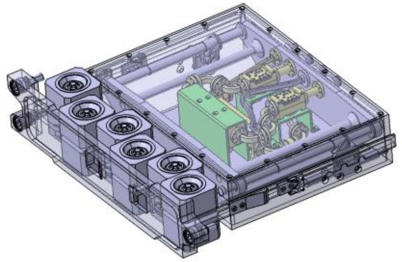
During plasma operation: Sniffer probe monitors gyrotron power & spectrum

Between plasma operations:
Calibration system checks alignment of Receiver TLs using ex-vessel source and receivers







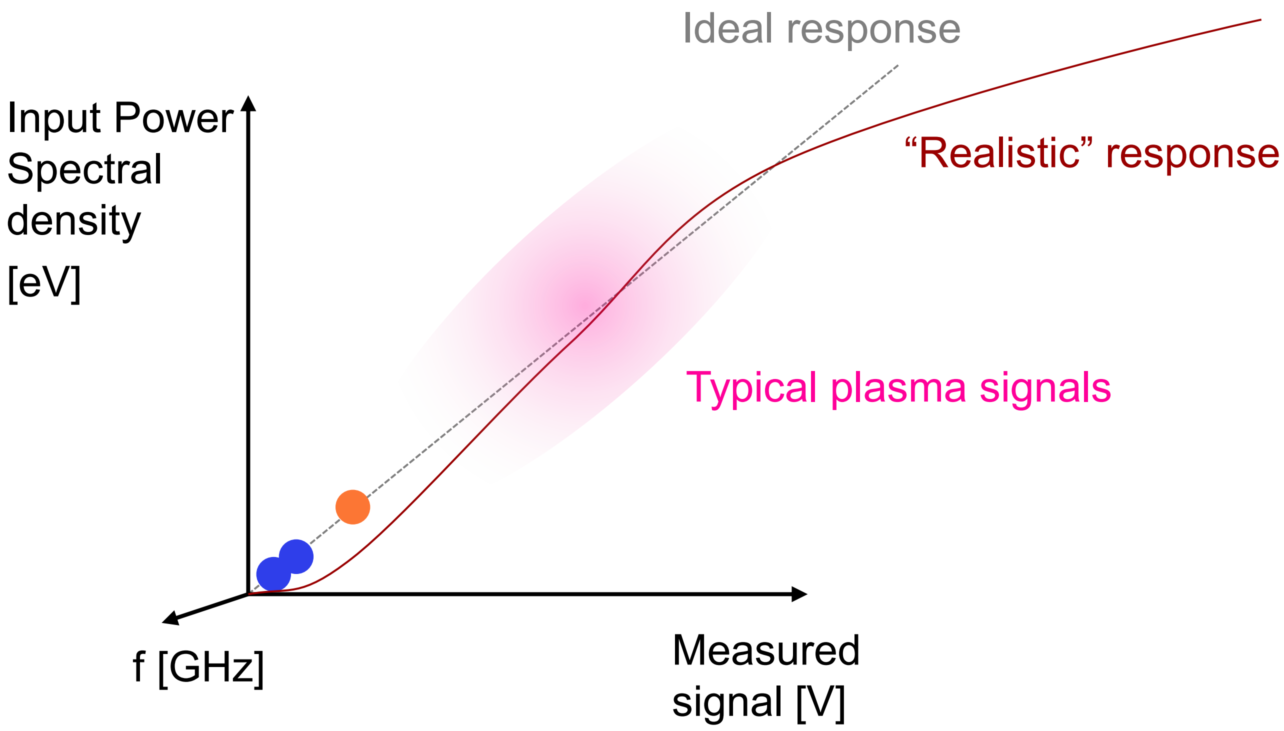


Additionally, 13 thermocouples monitors the in-vessel components

5. Calibration procedure and caveats

Background for calibration principle

- Liquid Nitrogen calibration too slow and low-power
- Avoid using an in-vessel hot source
- Plasma ECE can be near zero* (for 55-65 GHz) at normal operating conditions



*J. Rasmussen *et al, Plasma Phys. Control. Fusion* **61** (2019)

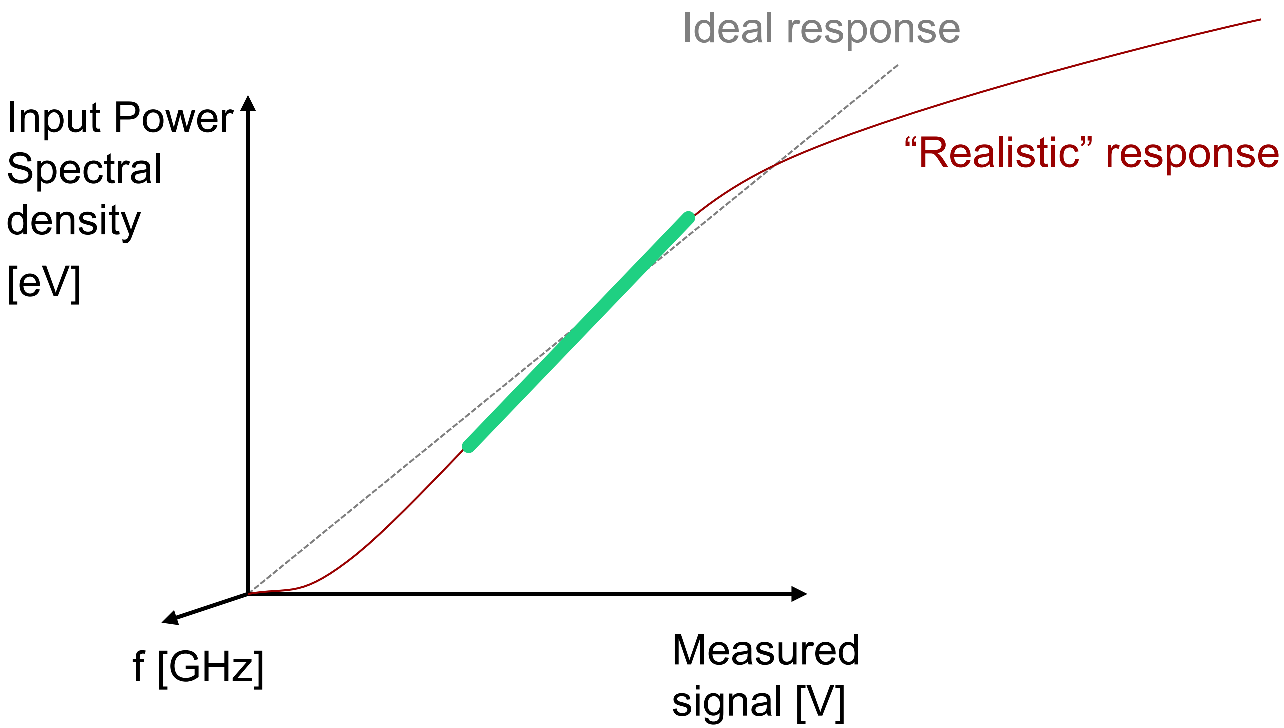
Solution

Ex-vessel tunable microwave source emitting signal into:

- A frequency/power meter
  - ➢ Known calibration signal

- The receiver electronics
  - ➢ Calibration of the back-end

- The plasma facing mirror
  - ➢ Calibration of the transmission line by comparison to reference



Power level (and frequency) of the source can be chosen to relevant ranges

Calibration procedure

- Prior to ITER operation the complete transmission lines are calibrated using the in-situ calibration system – Used as later reference for verifying the receiver TLs integrity
- Prior to operational day, a full calibration cycle can be performed – comparing to reference
- In-between plasma discharges, calibration may be perfomed
- The CTS calibration may be supplemented with ECE measurements for e.g. 1/3 B_0
  - And for full field B_0 all receivers should pick-up the same ECE signal (varying in f, possibly very low level*)

<u>Identified challenge:</u>

- Ex-vessel TLs are not evacuated -> transmission loss due to O2 absorption lines ~61 GHz
- Compensated in the initial calibration – however, evacuated TLs would have been nice…

*J. Rasmussen *et al, Plasma Phys. Control. Fusion* **61** (2019)

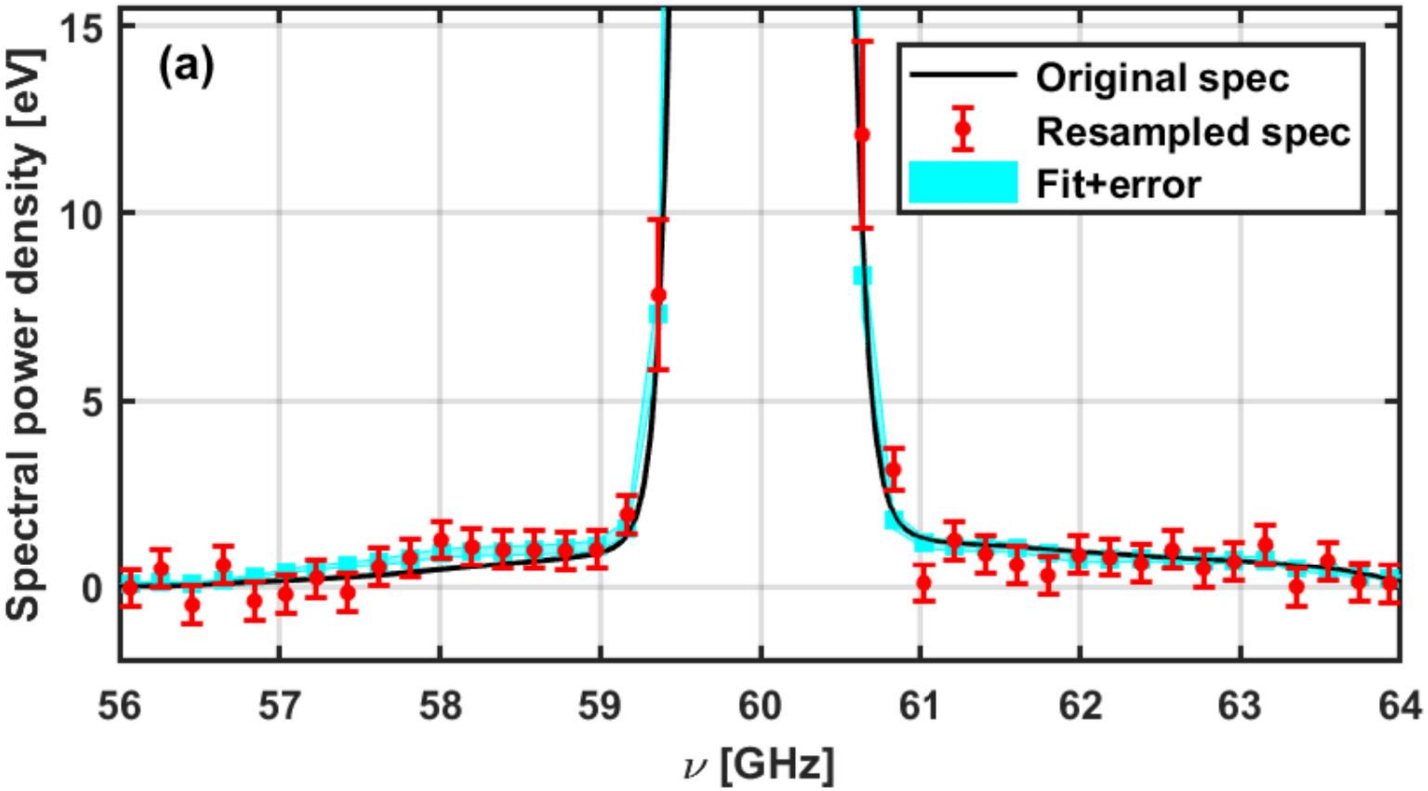
Monochromatic sources VS amplifier loading

- Electronics almost never behave like the “ideal”. Effects include:
  - Gain compression effects
  - Power supply load
  - Bias
  - Distortion
  - Higher temperatures, and thermal floor
  - Non-linearities?

- Also true for fast digitizers (depending on Signal/Dynamic range)

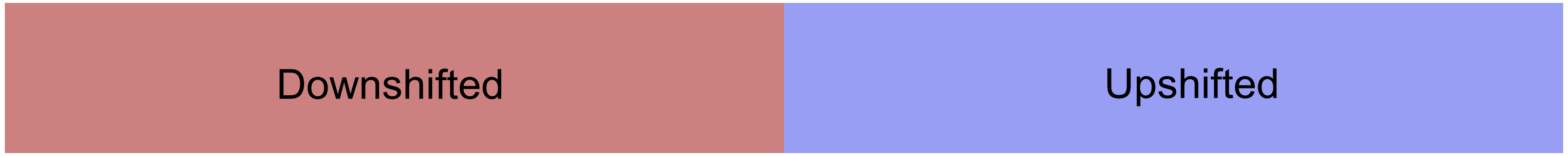
- Single frequency input / Low load representative of broadband plasma signals?
  - Favor broadband + single peak

Plot from J. Rasmussen et al.(2019). https://doi.org/10.1088/1741-4326/ab2f50

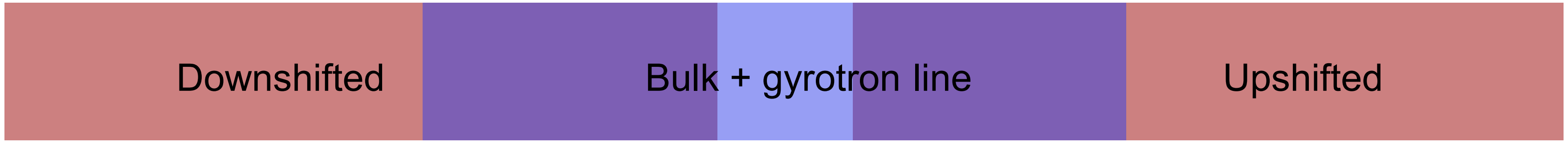


2 VS 3 digitizers per view

1 LO,
No cross-calibration



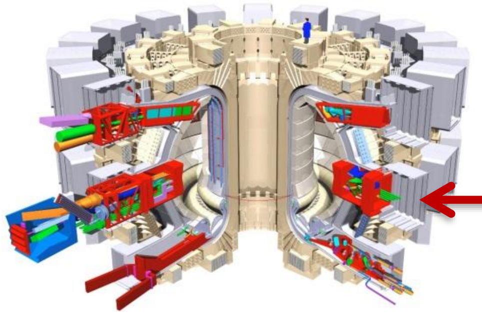
3 LOs,
Overlapping frequency ranges,
≠dynamic ranges bulk/wings
More data

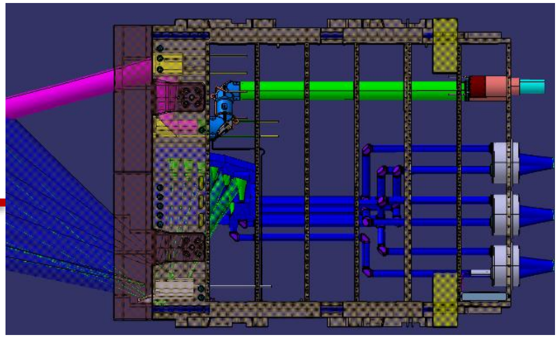


Summary and outlook

- ITER CTS front-end has passed the Final Design Review and will fulfil measurement requirements for alpha spectrum/density and fast ion spectra
- New continuous ultrafast (10+ GS/s) digitizers enable Filterbank-like use, with bit-depths progressing (now 12 bits), and on-board processing capabilities for e.g. real-time FFT
- In-situ calibration system is part of design
  - External tuneable (power and frequency) source
  - Calibration and transmission line integrity checks at representative ranges
  - Choice of digitization setup can affect calibration reliability

Additional slides





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L. Sanchez, R.M. Ballester et al
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Work done under contract F4E-FPA-393 between F4E and the DTU/IST Consortium
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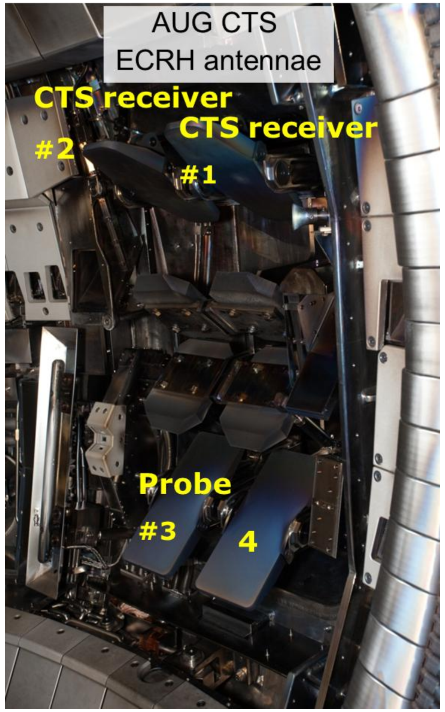
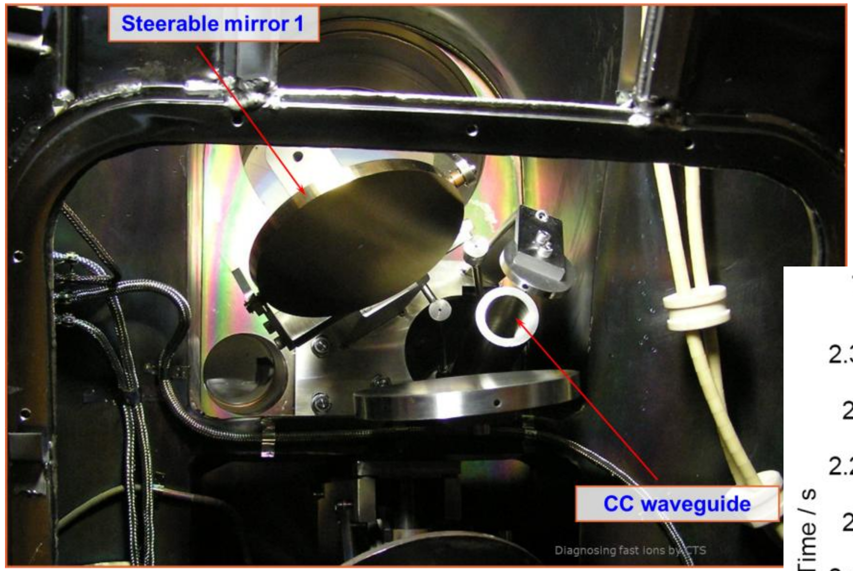
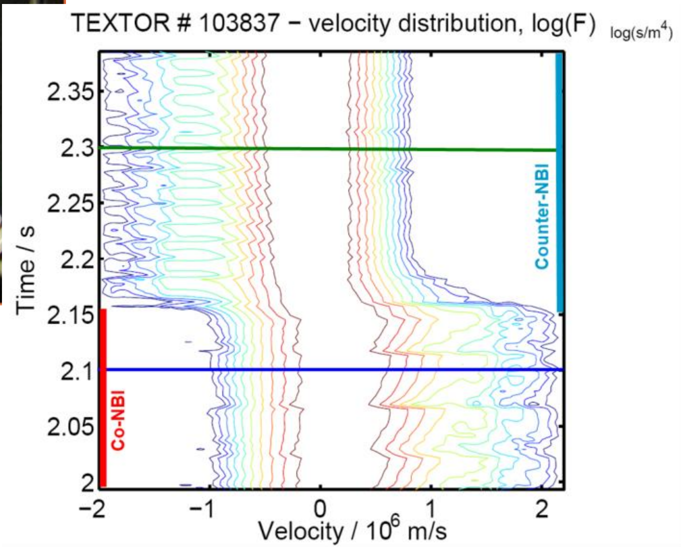
Fast- and bulk-ion CTS diagnostics



- Depending on setup and scattering geometry the CTS spectrum can be sensitive to the fast and/or the bulk ion features in the velocity distribution function.
- Demonstrated on several present day machines; e.g.:
  - TEXTOR
  - AUG
  - W7-X
  - LHD
  - and HL-2A (upcoming)





❖ S.B. Korsholm et al. NIMA **623** (2010)
❖ H. Bindslev et al, PRL **97** (2006)
❖ S.B. Korsholm et al, PRL **106** (2011)
❖ F. Meo et al, RSI **79** (2008)
❖ S.K. Nielsen et al, Phys. Scr. **92** (2017)
❖ M. Stejner et al, PPCF **59** (2017)
❖ D. Moseev et al, RSI **90** (2019)
❖ M. Nishiura et al, Nucl. Fusion **54** (2014)
❖ W.C. Deng et al, JINST **17** (2022)

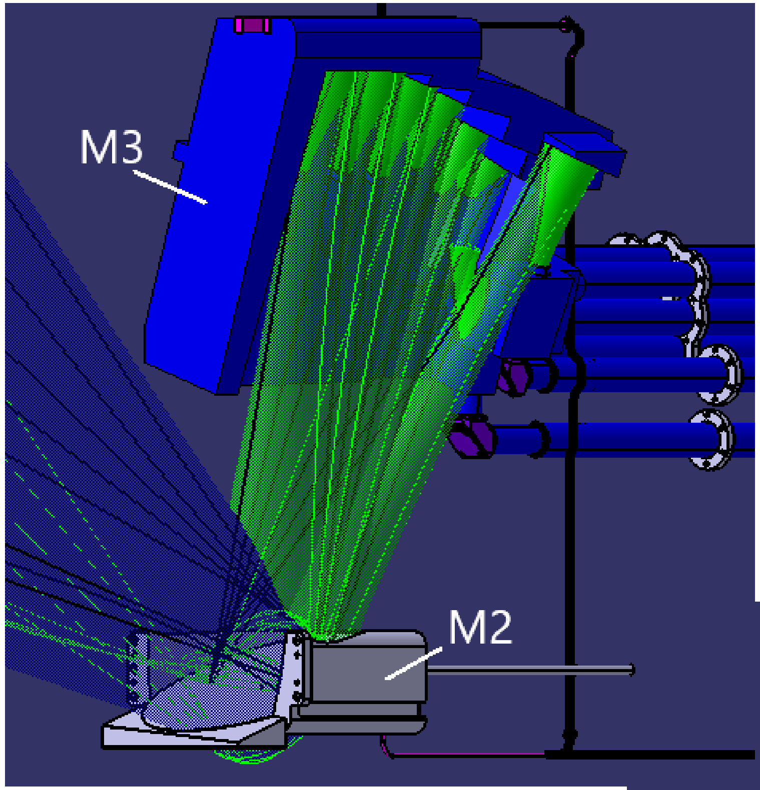
Design restrictions for a fast-ion ITER CTS diagnostic

- 1 MW gyrotron beam at 60 GHz (subharmonic to minimize ECE background noise) –> no absorption in the plasma
- Transmission of 1 MW probe beam in Ø88.9 mm waveguide through a resonant magnetic field in port plug -> *risk of breakdown inside in-vessel waveguide*
- Radiation from the plasma & absorption of gyrotron beam (~5 kW for plasma facing mirrors) -> cooling of components
- Neutron streaming through apertures in the first wall blanket ->

Diagnostic performance vs. loads on components and machine

- Design of mirrors to achieve diagnostic goal while being robust -> No moveable parts
- Restricted space in the allocated section of a port plug
- Restricted space at closure plate for transmission of microwaves

Closer view at plasma facing receiver mirror (M2)



Prerequisite that antenna pattern is relatively uniform. I.e. sufficient power reaching each secondary receiver mirrors (M3).