Topic: **Millimeter wave technologies for ECE and ECRH**

Fourier Transform based ECE systems for Real Time Tearing Mode Control* in Tokamaks©

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**Partner in the Trilateral Euregio Cluster*

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**See also talk B. Hennen et al., "Feedback control of tearing modes through ECRH with launcher mirror steering and power modulation using a line-of-sight ECE diagnostic" at Wednesday 14:00*

Outline

Fourier Transform (FT) based ECE systems for Real Time Tearing Mode Control* in Tokamaks

- **Definition: FT based ECE system**
- **Motivation for FT based ECE systems**
- **Theoretical Characteristics**
- **Challenge and solution**
  - ✓ Implementation of the line-of-sight conventional- and FT-ECE systems on TEXTOR*
  - ✓ Proof of principle on TEXTOR, measured by pilot FT System:
    1) ECRH scattering
    2) ECE emission
- **Conclusion and Outlook**

**See also talk B. Hennen et al., "Feedback control of tearing modes through ECRH with launcher mirror steering and power modulation using a line-of-sight ECE diagnostic" at Wednesday 14:00.*

Definition Fourier Transform ECE systems

Frontend at all ECE systems:

ECE RF signal from USB or LSB (by HP or LP filter) down converted by mixers and LO to one or several IF bands and amplified

Conventional ECE system:

IF bands splitted in several smaller 2nd IF frequency bands and fed to video detectors with amplifiers connected to slow ADCs

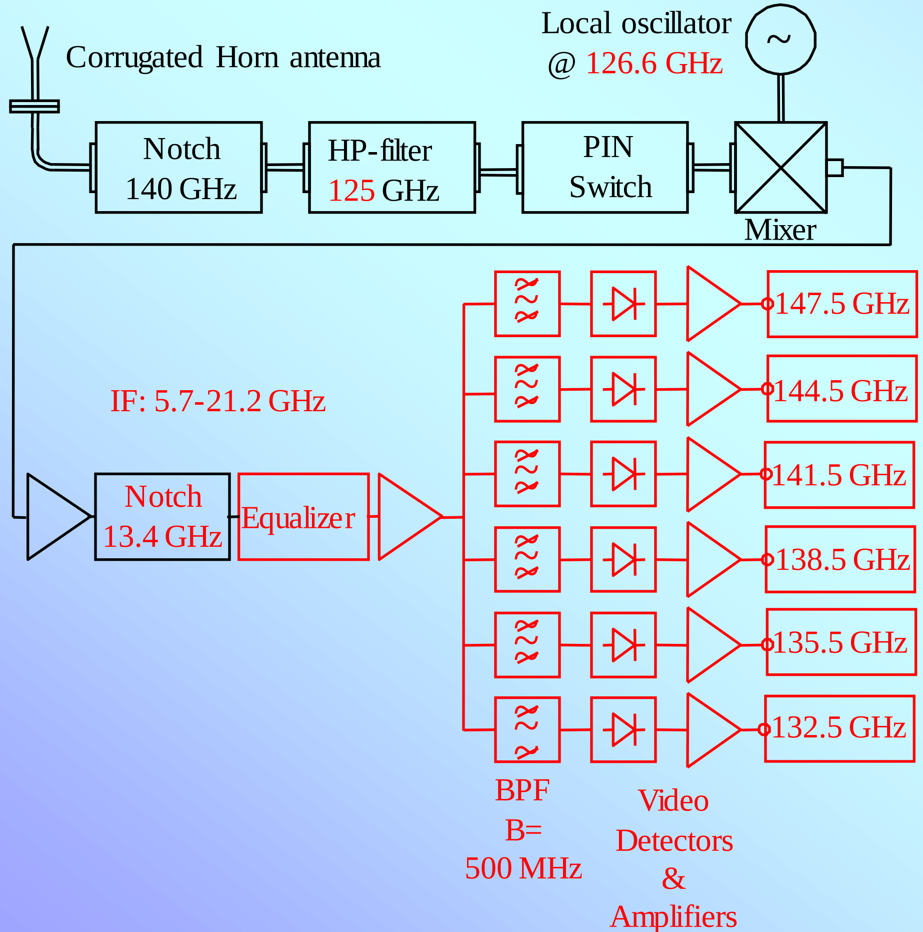
Fourier Transform ECE system:

IF bands are directly digitized by Fast Giga sample ADC's (no video detection and conservation of ECE frequency phase)

- ✓ Real-time or off-line data processing to extract spectra as function of time

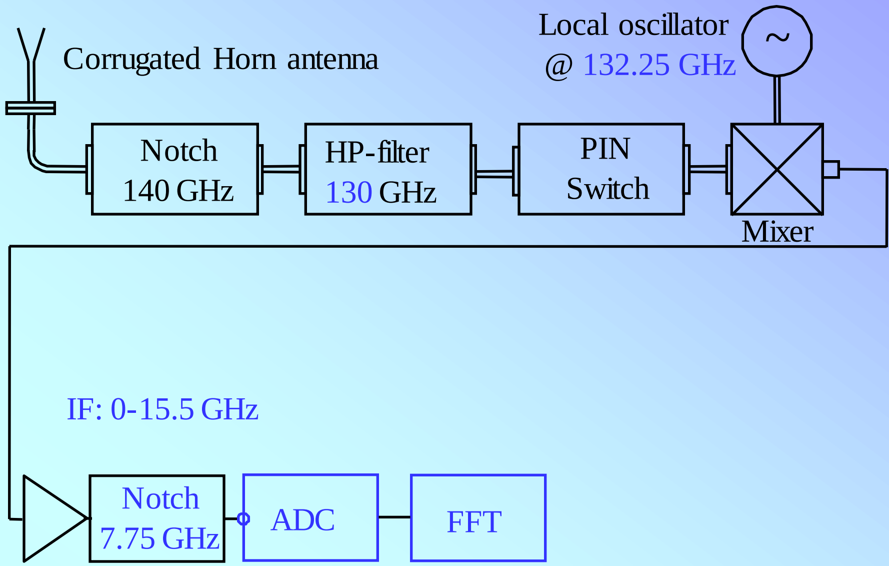
Definition Fourier Transform ECE systems

Example
Conventional ECE system:



Only limited nr. of Channels

Equivalent
Fourier Transform ECE system:



one ADC
> 31 Gsample
e.g. or alternatively
4 ADCs of 8 Gsample
and quad splitter,
3 mixers, amplifiers &
LOs

Thousands of Channels

Motivation

Conventional ECE:

- ❖ (With limited channels) Works fine with fixed spatial and temporal resolution
- ➢ Observed anomalous ECRH scattering in specific phases of magnetic islands

FT ECE system (to study phenomenon in detail):

- ✓ Frequency resolution can be exchanged in trade-off with time resolution of plasma. Possible within the system bandwidth to:
  - ✓ Have flexible time/spatial resolution
  - ✓ Dynamically zoom in on certain plasma positions or plasma events
- ✓ Became possible by recent development of Gsample/s ADCs
- ✓ Example: Real time FT spectrometer ECE systems could be used as an adaptive sensor for MHD stability control

Theoretical Characteristics

Qualifiers of ECE System

$$T_{rec} = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \ldots \qquad T_{sys} = \left(L_{wg} - 1\right) T_0 + L_{wg} T_{rec}$$

$$P_{\min sys} = k_B B_{IF}\, T_{sys} \sqrt{\frac{2 B_{vid}}{B_{IF}}} \qquad \frac{\Delta T_{ECE}}{T_{av\ ECE}} = \sqrt{\frac{2 B_{vid}}{B_{IF}}}$$

ECE (for plasma control) Design Criteria:

- ❖ Real time control loop frequency
  - ➢ Video Bandwidth: B_{vid}
- ❖ Thermal- (& wave)-noise ratio on ECE signal (eg ~few %)
  - ➢ Relative fluctuation ratio to average ECE: $\sqrt{2 B_{vid} / B_{IF}}$
- ❖ Spatial resolution and range :
  - ➢ IF Bandwidth: B_{IF}
  - ➢ Total ECE receiver frequency range gives number of channels

Theoretical Characteristics

Conventional ECE system

Fourier Transform ECE system

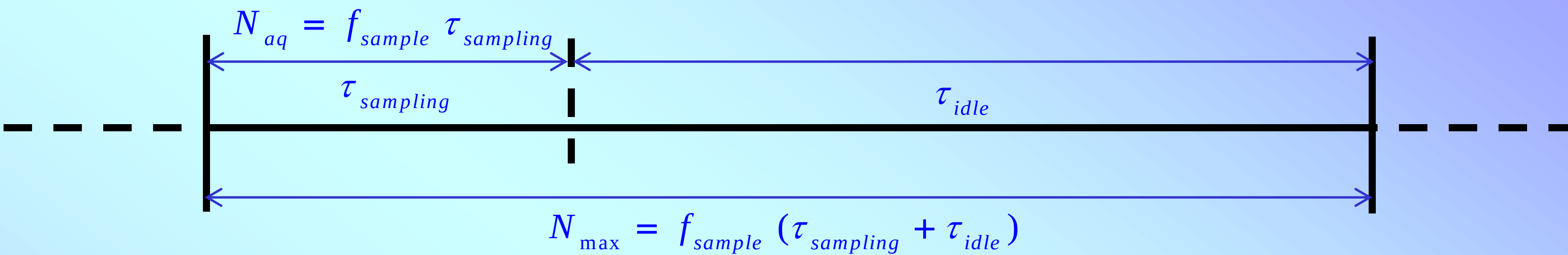
$$P_{\min conv\ ECE} = k_B B_{IF}\, T_{sys} \sqrt{\frac{2 B_{vid}}{B_{IF}}}$$

$$\frac{\Delta T_{ECE}}{T_{av\ ECE}} = \sqrt{\frac{2 B_{vid}}{B_{IF}}}$$

?

$$\frac{P_{\min FT\ ECE}}{P_{\min conv\ ECE}}$$

Fourier Transform ECE system



Acquisition for plasma control of FT ECE only feasible through reduction of data flow by blockwise data acquisition: In practice: $N_{aq}<N_{max}$ because idling time, $\tau_i >0$, is introduced

$$B_{vid} = \frac{1}{2\,\tau_{sampling}}$$

$$B_{IF} \geq \Delta f = f_{sample} / N_{aq}$$

$$P_{\min FT\,ECE} = \frac{k_B\, f_{sample}\, T_{sys}\sqrt{n}}{N_{aq}}$$

$$B_{IF} = n\,\Delta f$$

$$\frac{\Delta T_{ece}}{T_{av\,ECE}} = \frac{1}{\sqrt{n}}$$

$$B_{vid\;conv\;ECE} \cong B_{trig} = \frac{1}{2\left(\tau_{sampling} + \tau_{idle}\right)}$$

$$\frac{P_{\min FT\,ECE}}{P_{\min conv\;ECE}} = \sqrt{\frac{\tau_{sampling} + \tau_{idle}}{\tau_{sampling}}} = \sqrt{\frac{N_{max}}{N_{aq}}}$$

Theoretical Characteristics

Practical ECE FT 8 Gsample/s system ADC properties with current proven technology

Time domain samples	Frequency Resolution [MHz]	Spectrum Acquisition time [ns]	Video Bandwidth [kHz]	Maximum Retrigger Frequency [kHz]	Idle Time [ns]	Minimal Power conv. ECE [dB]	Data Transfer [Msample/s]	$\frac{\Delta T_{ECE}}{T_{av\ ECE}}$ B_{IF}=250 MHz
80	100	10	50,000	200	4990	-13.5	16	63%
800	10	100	5,000	66.25	14994	-10.9	53	20%
4,000	2	500	1,000	18.75	52833	-10.1	75	8.9%
8,000	1	1,000	500	10	99000	-10.0	80	6.3%
60,000	0.13	7,500	67	1.083	915577	-10.5	65	2.3%
160,000	0.05	20,000	25	0.313	3180000	-11.0	50	1.4%
320,000	0.025	40,000	13	0.125	7960000	-11.5	40	1.0%

interpolated

✓**Example:**

➢Suppose NTM rotation 1 kHz Design: B_{IF}= 500 MHz and B_{vid}> 5 kHz

✓**Best Solution:**

➢Retrigger rate=10 kHz B_{vid}=500 kHz and sum 500 frequency domain samples results $\Delta T_{ECE}/T_{av\ ECE}$= 4%

Theoretical Characteristics

Noise temperature of ADC

Dependent on:

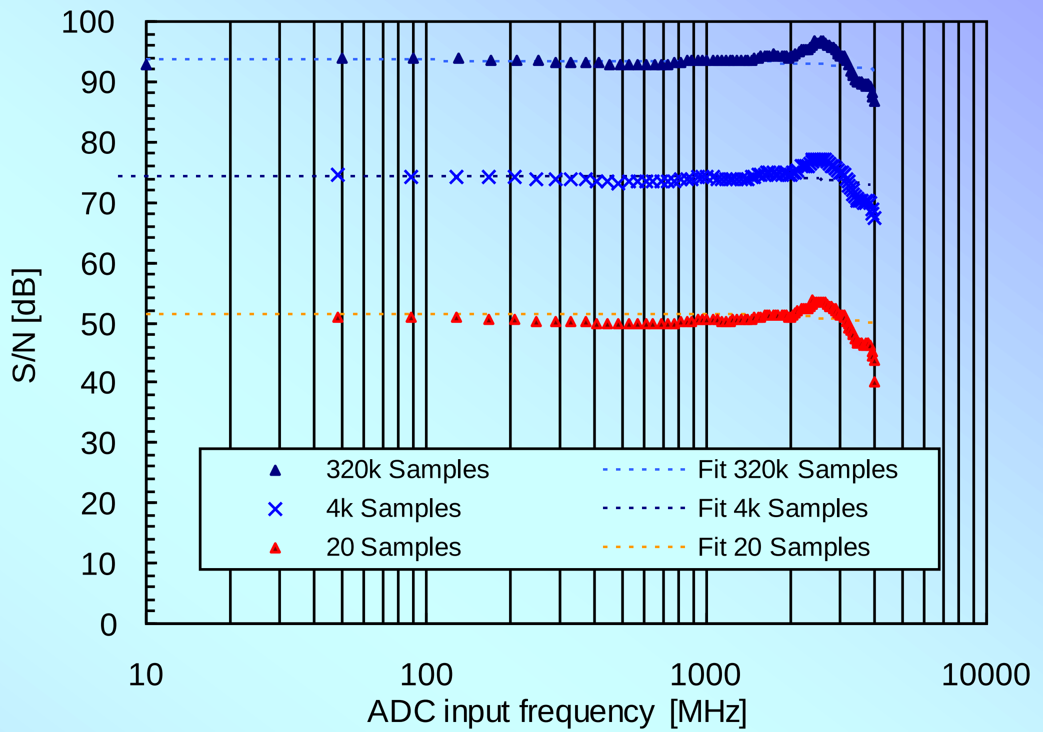
- FT Block size, N (dynamical gain)
- Effective number of bits, b (dc)
- Sampling window Jitter time, σ
- ADC internal amplifier/buffer

$$SNR(f) = 10\log\left\{\frac{3\,2^{2b}}{2+3\left(2^{b}2\pi f\sigma\right)^{2}}\frac{N}{2}\right\}$$

$$P_{\min ADC}(f) = \left\{10^{\left(P_{clip}-SNR(f)\right)/10}\right\}/1000$$

$$T_{ADC}(f) = \frac{P_{\min ADC}(f)}{k_B B_{IF}}$$

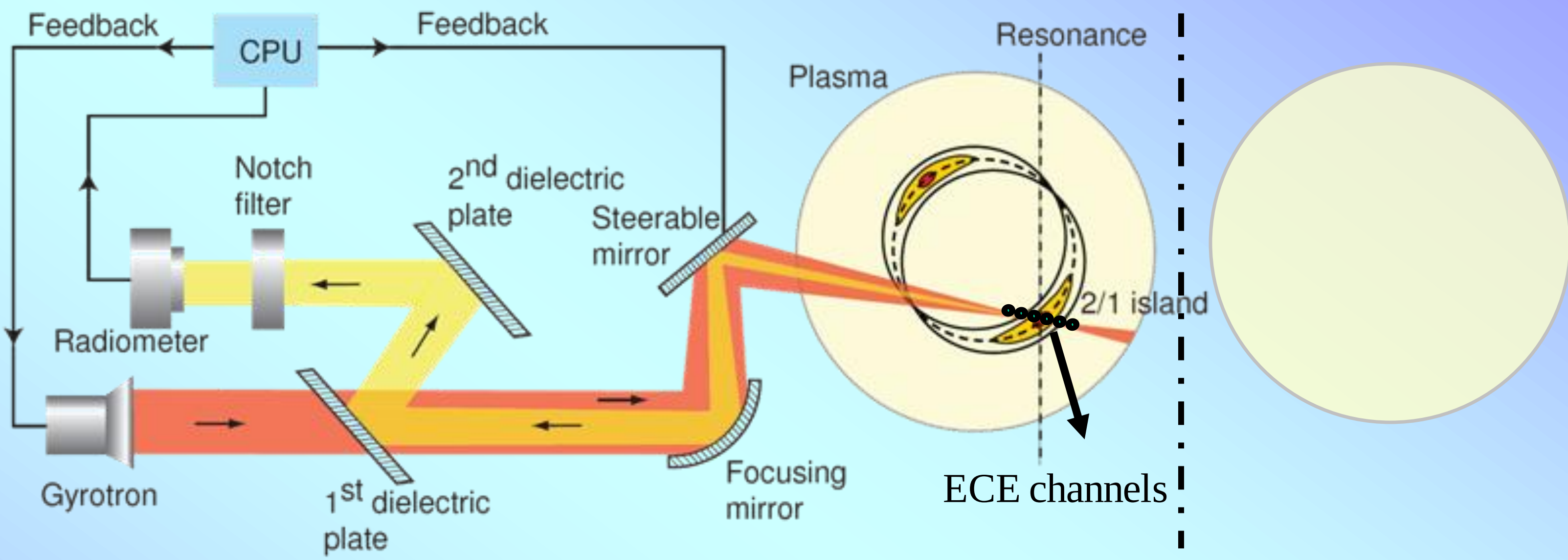
Measurement of Agilent 8 Gsample/s ADC



Effective number of bits is 6.6 of 10 (dc) and the RMS jitter time is about 0.2 ps ADC amplifier/buffer has significant influence at maximum outer frequency limit

Implementation

In-Line ECE ON TEXTOR



- **In line ECE implemented on TEXTOR as sensor for MHD feedback control:**
  - ➢ ECE is coming from the **exact** position where the ECRH is deposited: actuator and sensor always aligned
- **Anomalous ECRH scattering observed in specific phases of magnetic islands**
  - ✓ FT ECE system implemented to study phenomenon in detail: test case for flexible resolution

Implementation

Final design of in-line ECE

ECRH from gyrotron

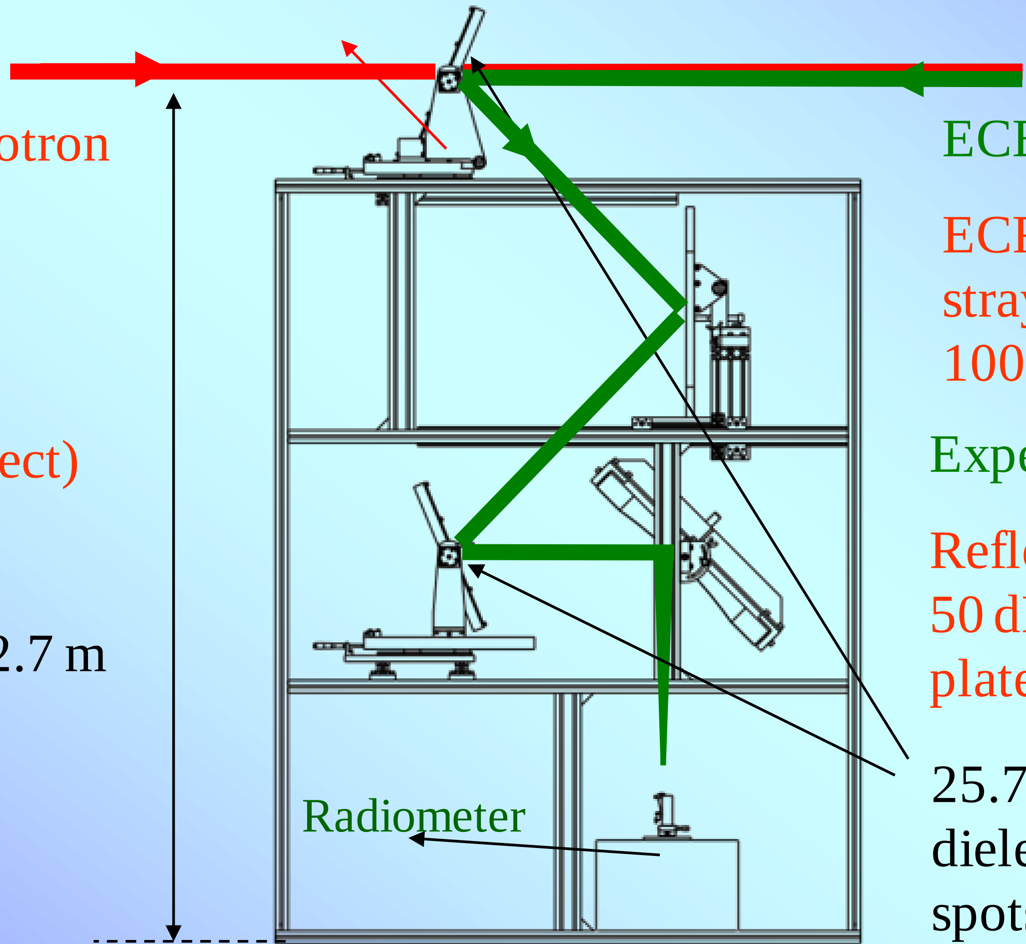
140 GHz

800 kW

10 seconds

(3 s for FB project)

Height = 2.7 m



Diagnostic box

ECE from plasma ~ 1nW

ECRH reflected and stray radiation, Estimate: 100 W

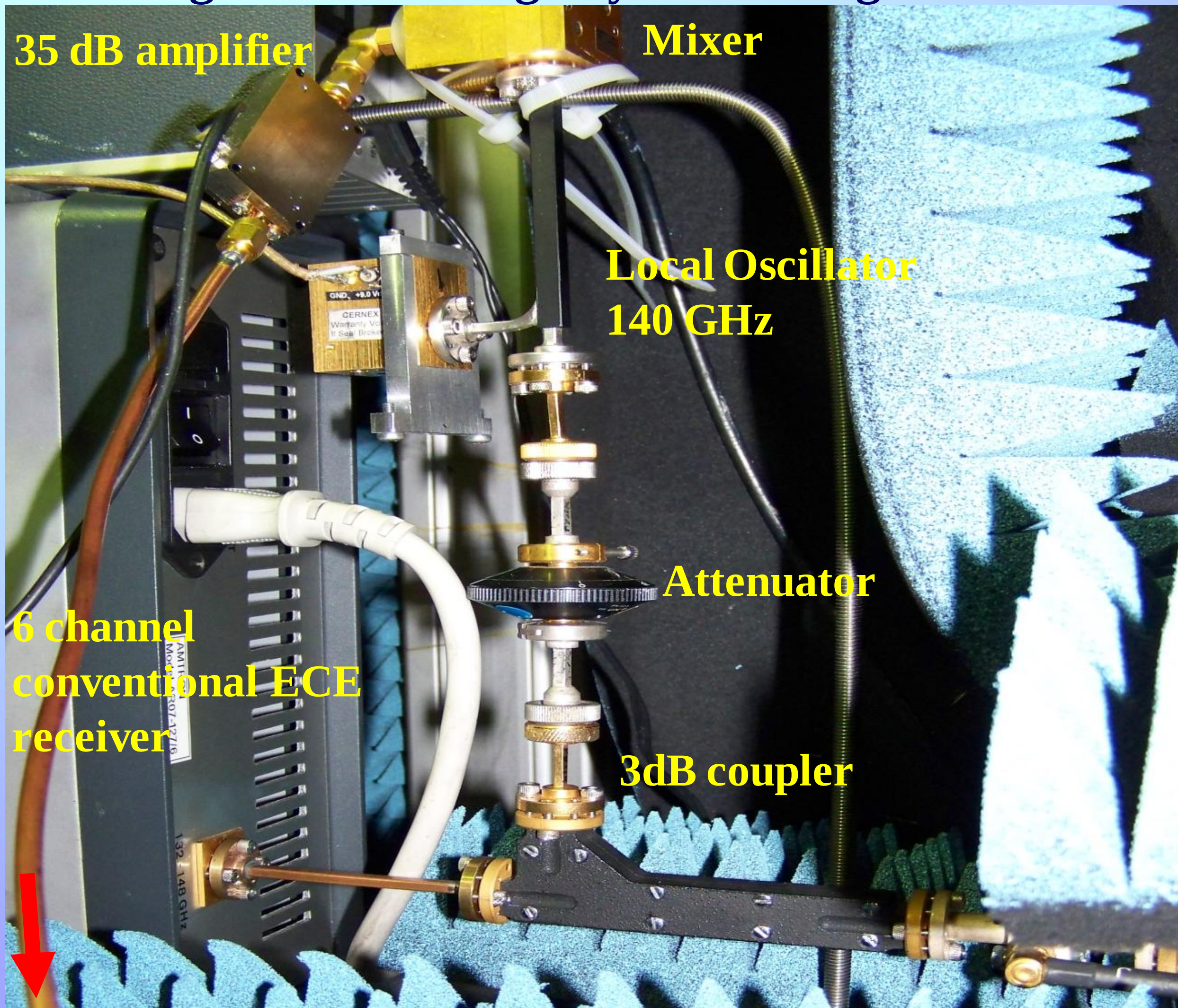
Expected ECE ~ 100 pW

Reflected ECRH down by 50 dB by two dielectric plates: ~ 1 mW

25.75 mm thick quartz dielectric plates (~0.1 m spotsize)

Implementation

Diagnostic: New high dynamic range FT receiver system (Double Sideband)



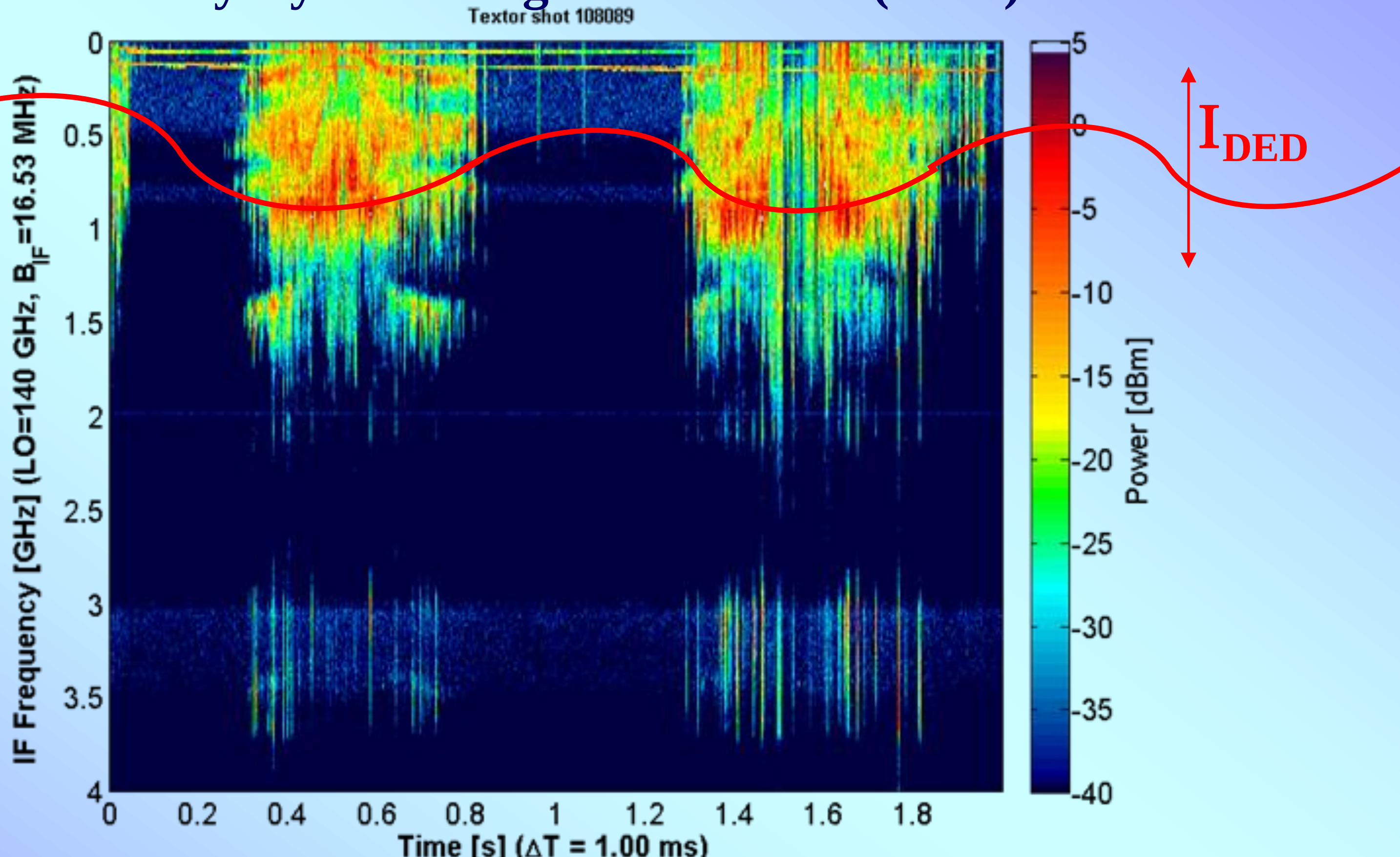
To ADC 8 Gs/s (4 GHz Bandwidth)

Proof of principle: results measured on TEXTOR

Time resolved ECRH Scattered radiation: slow movement of island by Dynamic Ergodic Divertor (DED)

Gyrotron signal(s) > 120 dB

8k freq domain samples 33 summed

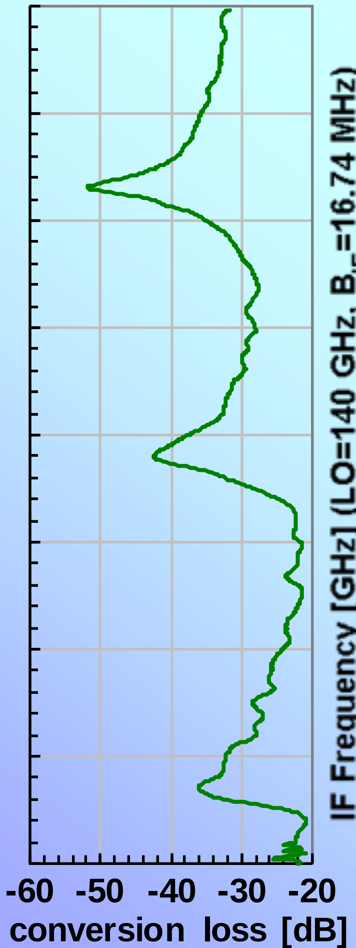


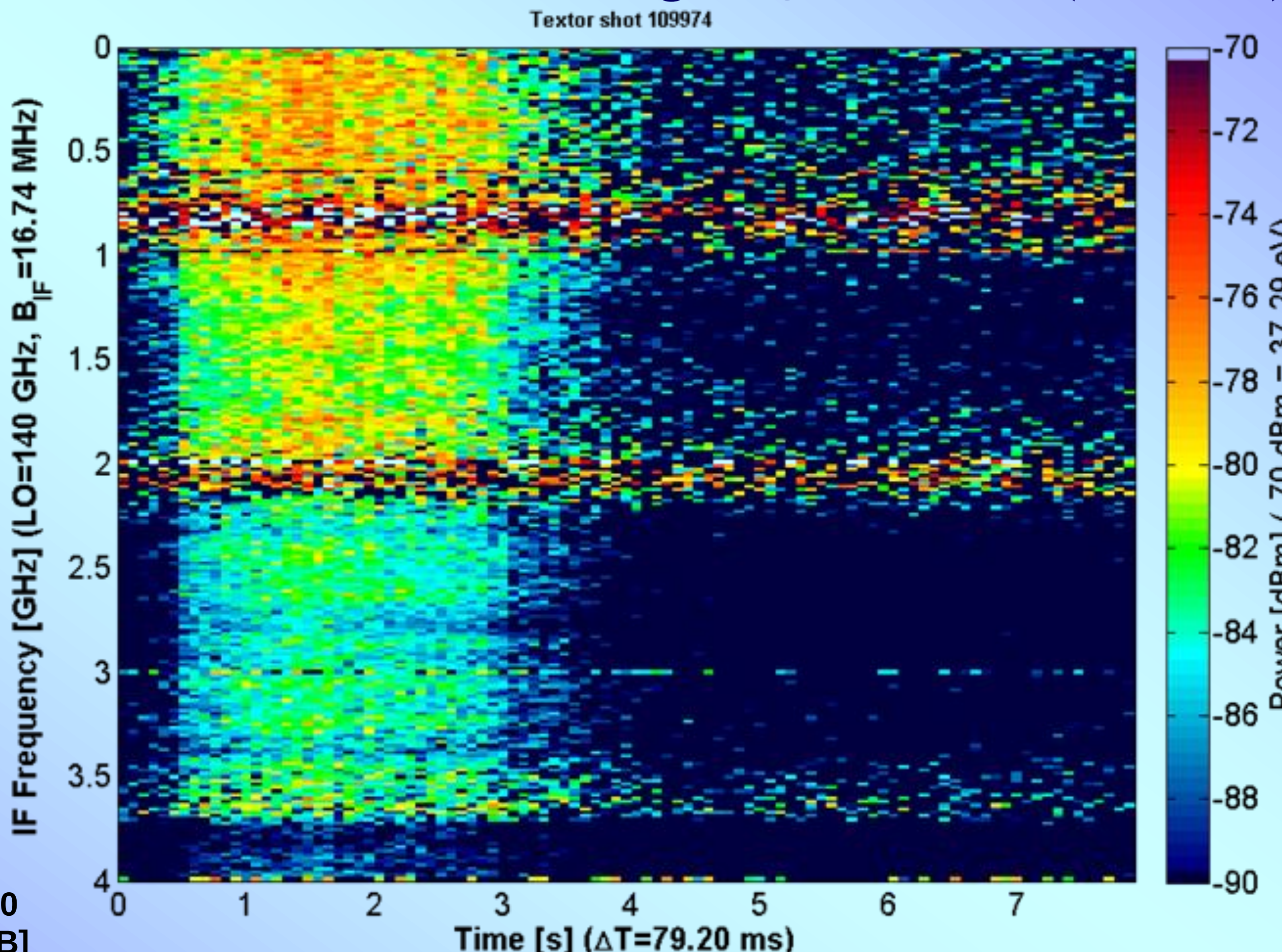
✔ Brand new physics: plasma EC-wave conversion related to Island rotation F. Westerhof et al. "Strong Scattering of High Power Millimeter Waves in Tokamak Plasmas with Tearing Modes", PRL103,.125001 (2009)

Correlate 100% with MHD: Island is moved back-and-fourth by DED with frequency of about 2 Hz and in the spectrum a symmetrical frequency changed is observed in time!

Proof of principle: results measured on TEXTOR

Time–resolved FT ECE signal @ no ECRH (Bt=1.9 T)





160k freq domain samples 666.7 summed ΔT_{ECE}= 4%

+15 dB Dielectric plates replaced by mirrors, omit Notch & coupler

- Signal quality marginal caused by high conversion loss of the mixer of the FT frontend and TEXTOR operational conditions of the day

Conclusion and Outlook

New ECE system with direct IF digitization: Fourier Transform ECE

- ✓ **Advantages:**
  - ✓ Flexible time/spatial resolution with optional dynamic zoom on certain plasma positions or events: possible application to adaptive sensing for MHD control
  - ✓ Wavelets analysis instead of FT is possible
- ✓ **By block-wise data acquisition a reduced minimal detected power compared to conventional systems (~10 dB)**
- ✓ **Limited range (4 GHz) FT system is tested on TEXTOR in line-of-sight concept**
  - ✓ Good ECRH scattering
  - ➢ Marginal ECE emission measured (due to frontend and operational conditions)
- ➢ **Next step to develop full range FT ECE/scatter system for control**
  - ➢ Minimize idling time and high performance frontend