THDA application for SOEC degradation monitoring

REACTT

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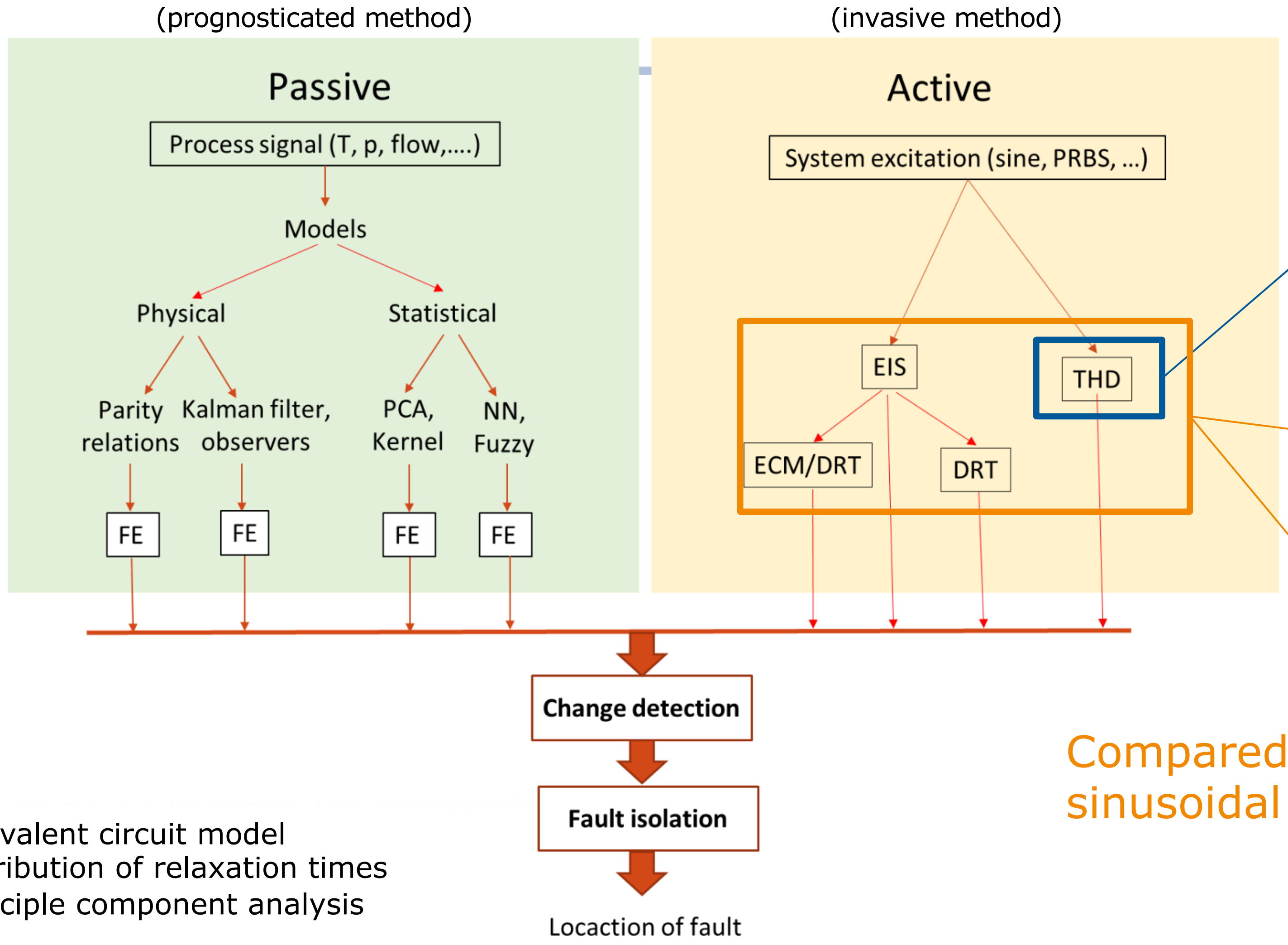
AVL List GmbH

Content – THDA application for SOEC degradation monitoring

General diagnosis strategy



AVL responsibility:
- implementation of THD

AVL accessibility:
- Testing raw data

Compared to EIS, THD requires sinusoidal perturbation

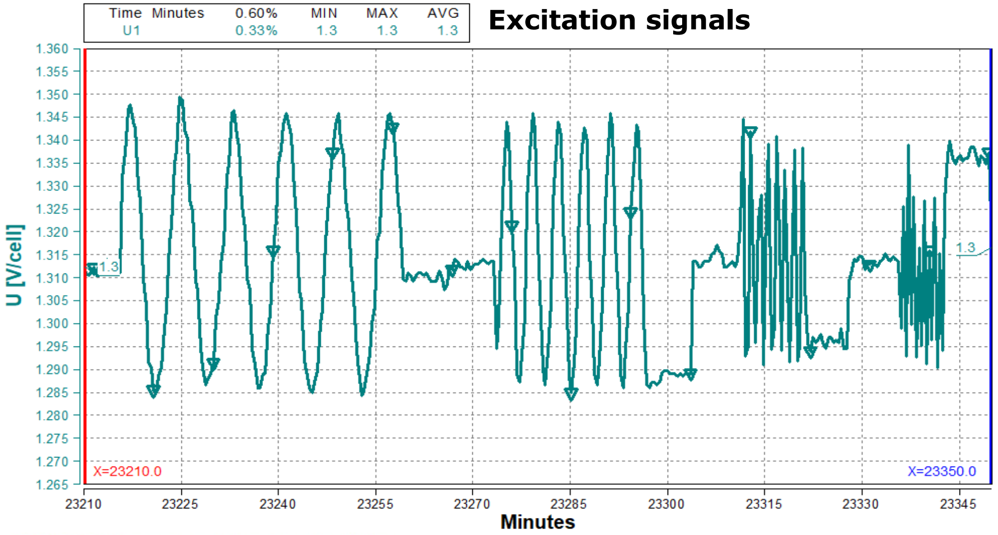
ECM… equivalent circuit model
DRT… distribution of relaxation times
PCA… principle component analysis

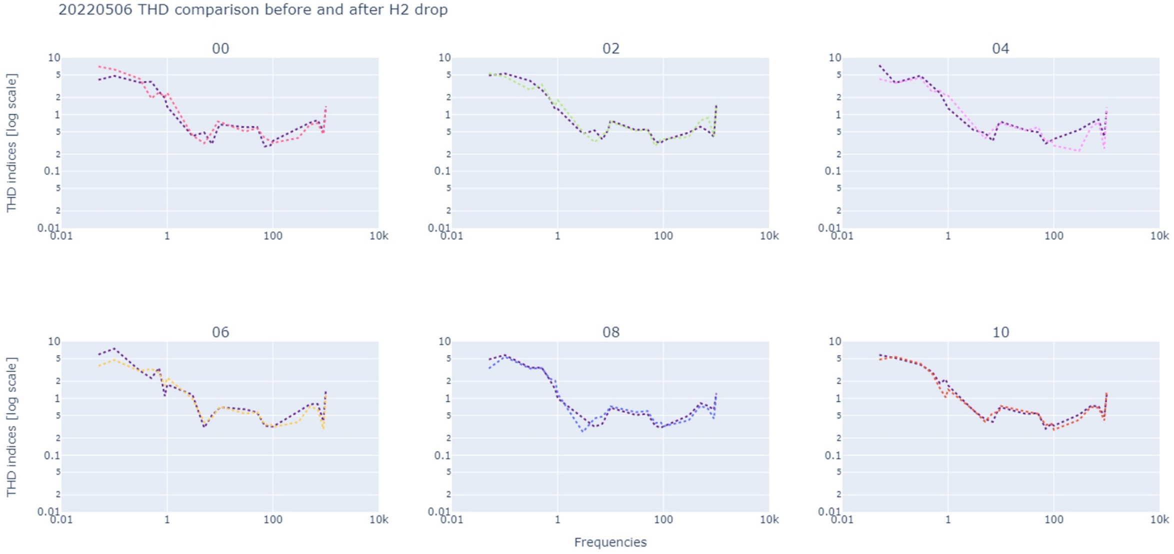
Total Harmonic Distortion (THD): technical description

- THD is used to analyze non-linearities/degradation in the system by sending a small excitation sinus signal into the system (e.g., X-Ion Device)
- Depending on the existing non-linearities in the stack polarization curve, harmonics of the excitation signal can be created, which distort the system response.
- Level of presence of these harmonics is calculated with THD index:

$$THD_{index} = \frac{\sqrt{\sum_{i=2}^{n} Y_i^{\,2}}}{Y_1} 100\ [\%]$$

- System response to the excitation needs to be analyzed in frequency domain in order to extract amplitudes of the harmonics.
- THD indices higher then 5% indicate presence of signal distortion which could reveal the presence of stack degradation or a harmful stack operation.



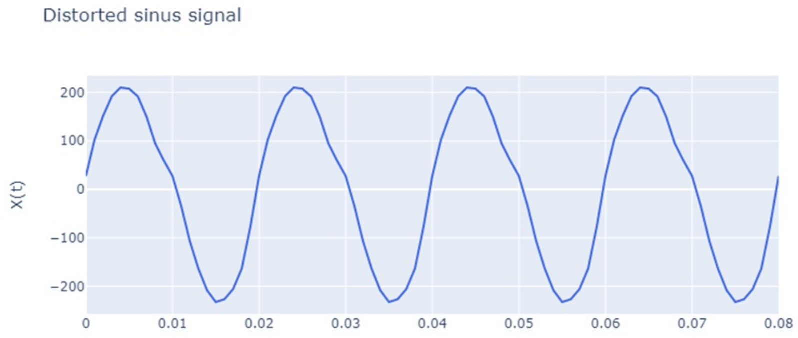


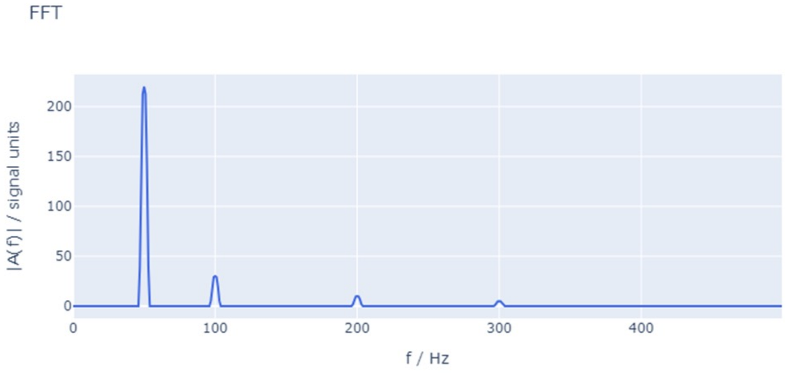
calculated THD indices for ex. signals with 22 different frequencies (H2 starvation test)

THD: Technical description

- THD analyze harmonic frequencies of a known base frequency. Harmonic frequencies are multiple integers of base frequency. THD index represents proportion of the combined intensity of the harmonics compered to the intensity of the base frequency.
- The intensities of harmonics and base frequencies are calculated with Discrete Fourier analysis, where each number in analysis result represent intensity of certain frequency in the signal.
- The occurrence of the harmonic frequency components in a signal are related to the non-linear distortion of the signal which in our case can be connected to nonlinearities in the fuel cell I-V relationship.
- Invasive excitation current and resulting voltage read out could be distorted by the nonlinearities in I-V relationship (fuel cell polarization).
- **Determination of excitation frequency and amplitude is crucial** for well implemented and calculated THD analysis for specific operational condition monitoring or degradation/fault isolation.

$$THD_{index} = \frac{\sqrt{\sum_{i=2}^{n} Y_i^2}}{Y_1} 100\ [\%]$$



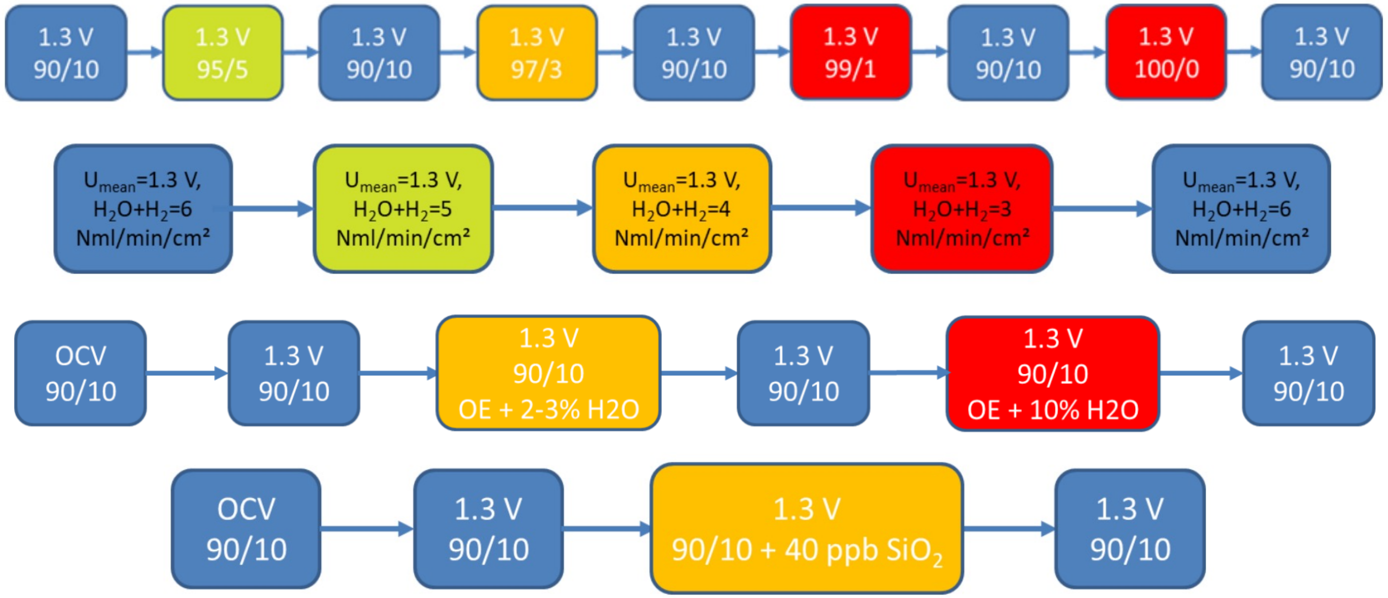


THD: Technical description

- The selection of the excitation signal characteristics, f_0 and A is based on the physical system and the phenomena, for which monitoring the algorithm is intended for
- Necessity for stack operation data in faulty and fault free operating modes for detection of:
  1. Frequency range where THD index is most visible
  2. Reasonable AC excitation percentage for detection of specific degradation:
     - i_{AC} amplitude should not be bigger then 10% of I_{DC} current to avoid creation of additional non linearities e.g., anode reoxidation.
     - Smaller current percentage usage has small chance of second and higher harmonics detection in output voltage signal
- Out of experiments on cell level a suitable values for f_0 and A should be determined, which will be then used for the system level experiments and monitoring
- Sampling frequency should always be: $f_s > 2 \cdot n_H \cdot f_0$ where n_H is number of observed harmonics
- **Challenge:** often the measured signal is not an integer number of periods which causes the spectral leakage effect
- Main drawbacks are the requirement for an invasive excitation signal and steady state operation of the system.

General testing approach

- Planned testing protocols:
  1. Inlet H_2 starvation
  2. High steam conversion
  3. Humidity in O_2 electrode
  4. Effect of silicon poisoning

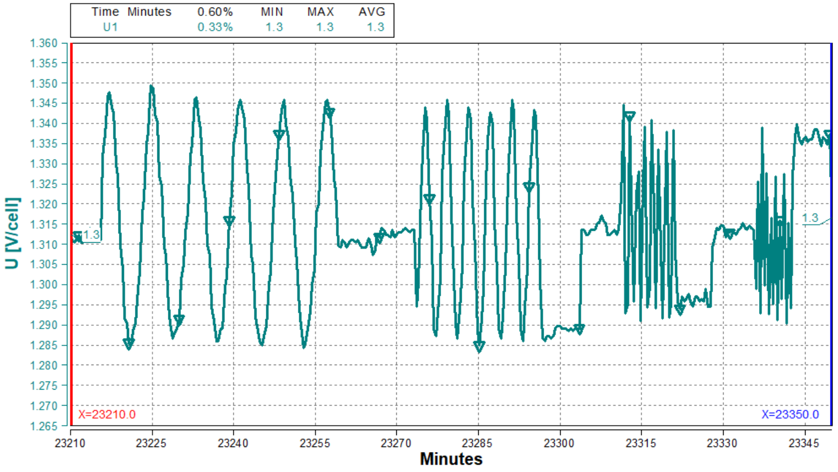


CEA H_2 starvation test

- CEA partly executed inlet H_2 starvation with only 95/5 and 100/0 water-hydrogen inlet ratio drops

- Every 2 hours excitation event was executed including 22 different excitation frequencies in rising order with same excitation amplitude

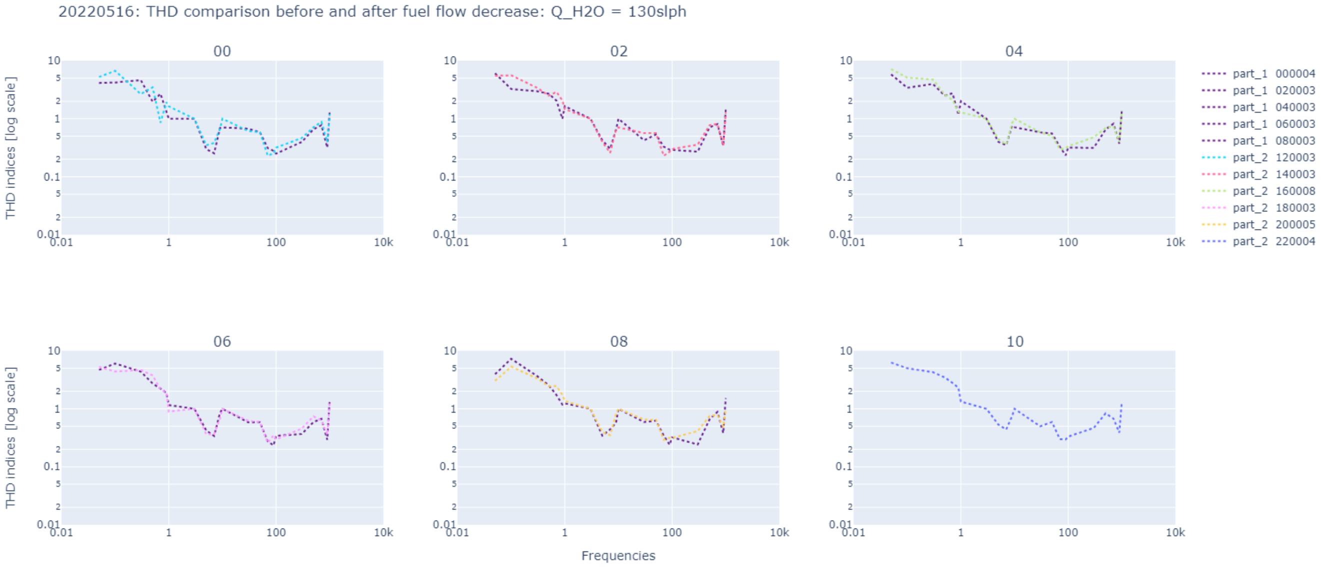
		HYDROGEN STARVATION AT DIFFERENT OPERATING TEMPERATURES AND FLOWRATES								
		first part of the meas. file		second part of meas. file			first part of the meas. file		second part of meas. file	
Date	Day	H2_1 [Nl/h]	H2O_1 [Nl/h]	H2_2 [Nl/h]	H2O_2 [Nl/h]	Time when shift took place	H2_ratio_1	H2O_ratio_1	H2_ratio_2	H2O_ratio_2
02.05.2022	20	17,3	135,1	8,2	135	11	0,13	0,87	0,06	0,94
03.05.2022	21	8,2	135	17,3	135	11	0,06	0,94	0,13	0,87
04.05.2022	22	17,4	135	0	135	12	0,13	0,87	0,00	1,00
05.05.2022	23	0	135	17,3	135,1	16	0,00	1,00	0,13	0,87
06.05.2022	24	17,2	135,1	0	135,1	11	0,13	0,87	0,00	1,00
07.05.2022	25	0	135,1	0	135,1	-	0,00	1,00	0,00	1,00
08.05.2022	26	0	135,1	0	135,1	-	0,00	1,00	0,00	1,00
09.05.2022	27	0	135,1	17,3	135,1	11	0,00	1,00	0,13	0,87
10.05.2022	28	17,3	135,1	0	135,1	11	0,13	0,87	0,00	1,00
11.05.2022	29	0	135	17,3	135	13	0,00	1,00	0,13	0,87
12.05.2022	30	17,3	135,1	17,3	135,1	-	0,13	0,87	0,13	0,87
13.05.2022	31	17,3	135,1	17,3	135,1	-	0,13	0,87	0,13	0,87
14.05.2022	32	17,3	135,1	17,3	135,1	-	0,13	0,87	0,13	0,87
15.05.2022	33	17,3	135,1	17,3	135,1	-	0,13	0,87	0,13	0,87

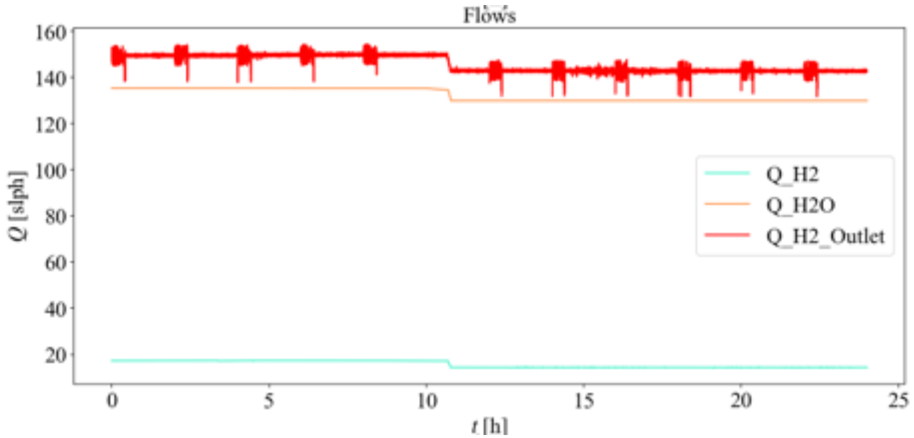


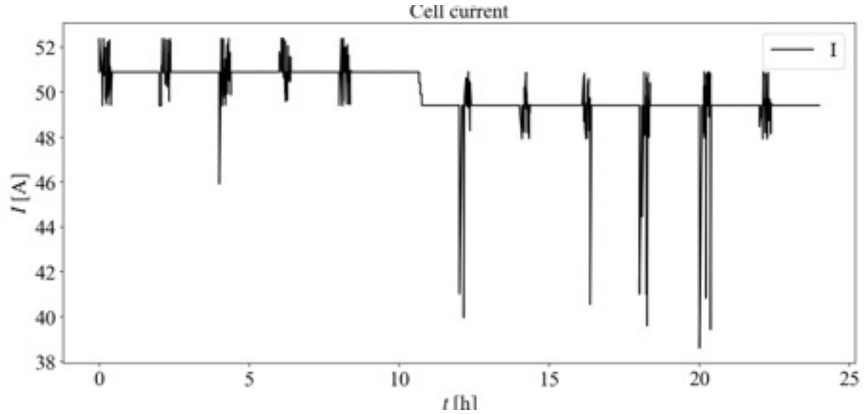
Frequency [Hz]	Duration of the excitation [s]
0.05	100.0
0.1	50.0
0.3	16.66624
0.5	10.0
0.7	7.1424
0.9	5.5552
1	5.0
3	1.66656
5	1.0
7	0.71424
9	0.55552
10	0.5
30	0.16664
50	0.4
70	0.28568
90	0.2222
100	0.2
300	0.06666
500	0.04
700	0.02856
900	0.02222
1000	0.02
3000	0.006665
5000	0.004

CEA High steam conversion

- CEA executed High steam conversion fully
- Every 2 hours excitation event was executed including 22 different excitation frequencies in rising order with same excitation amplitude

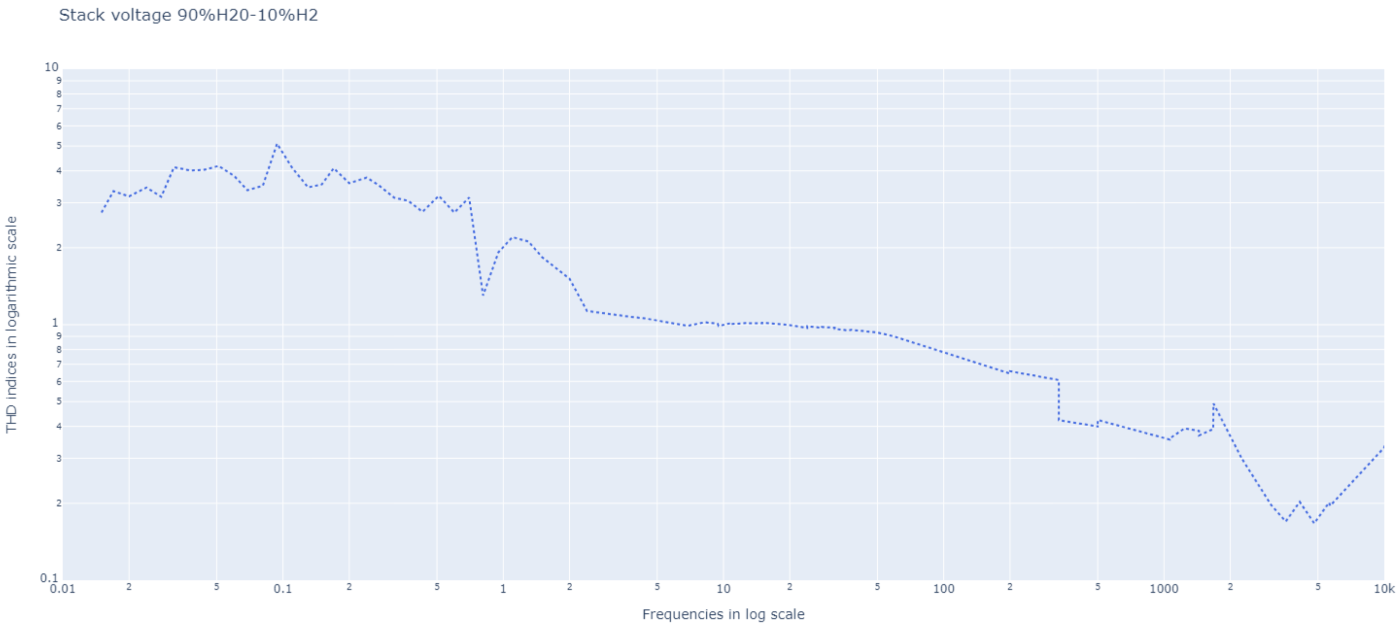




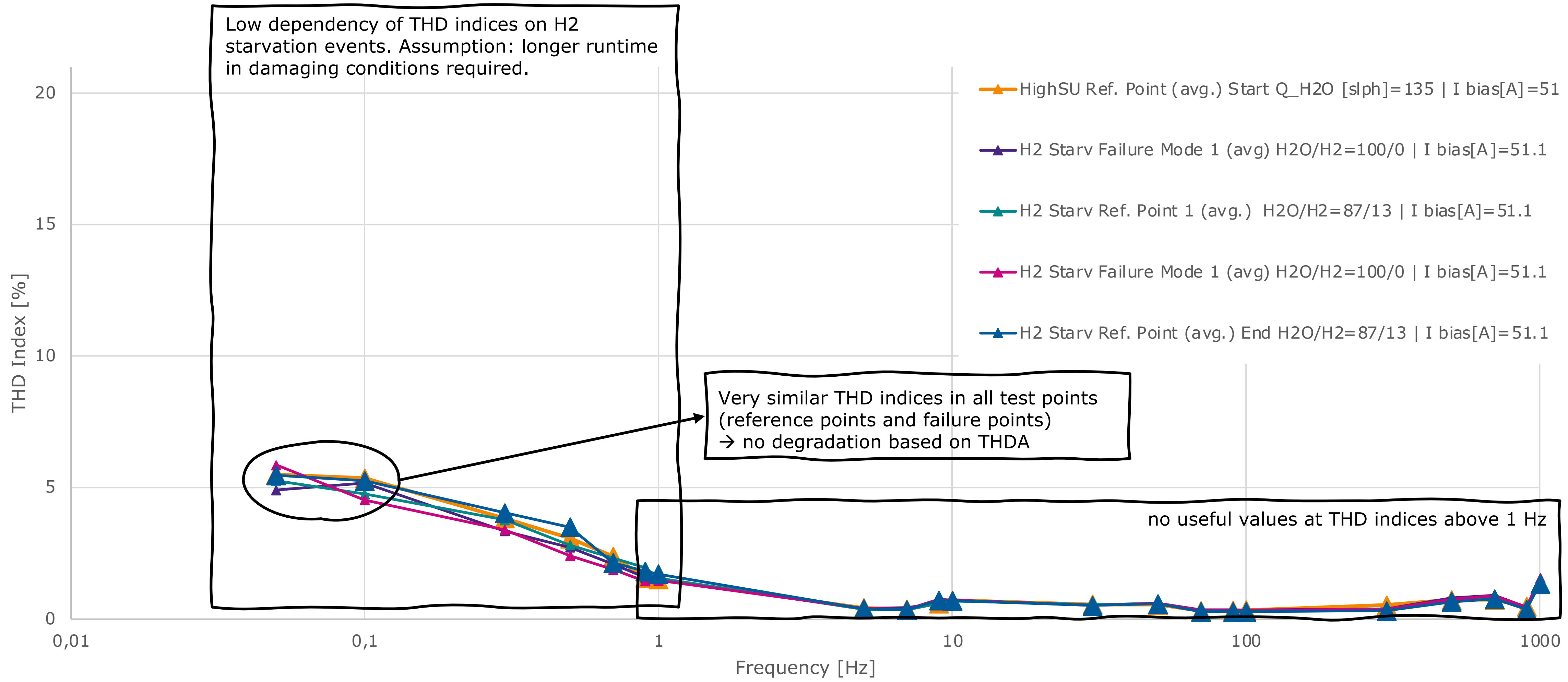


EPFL H_2 starvation test

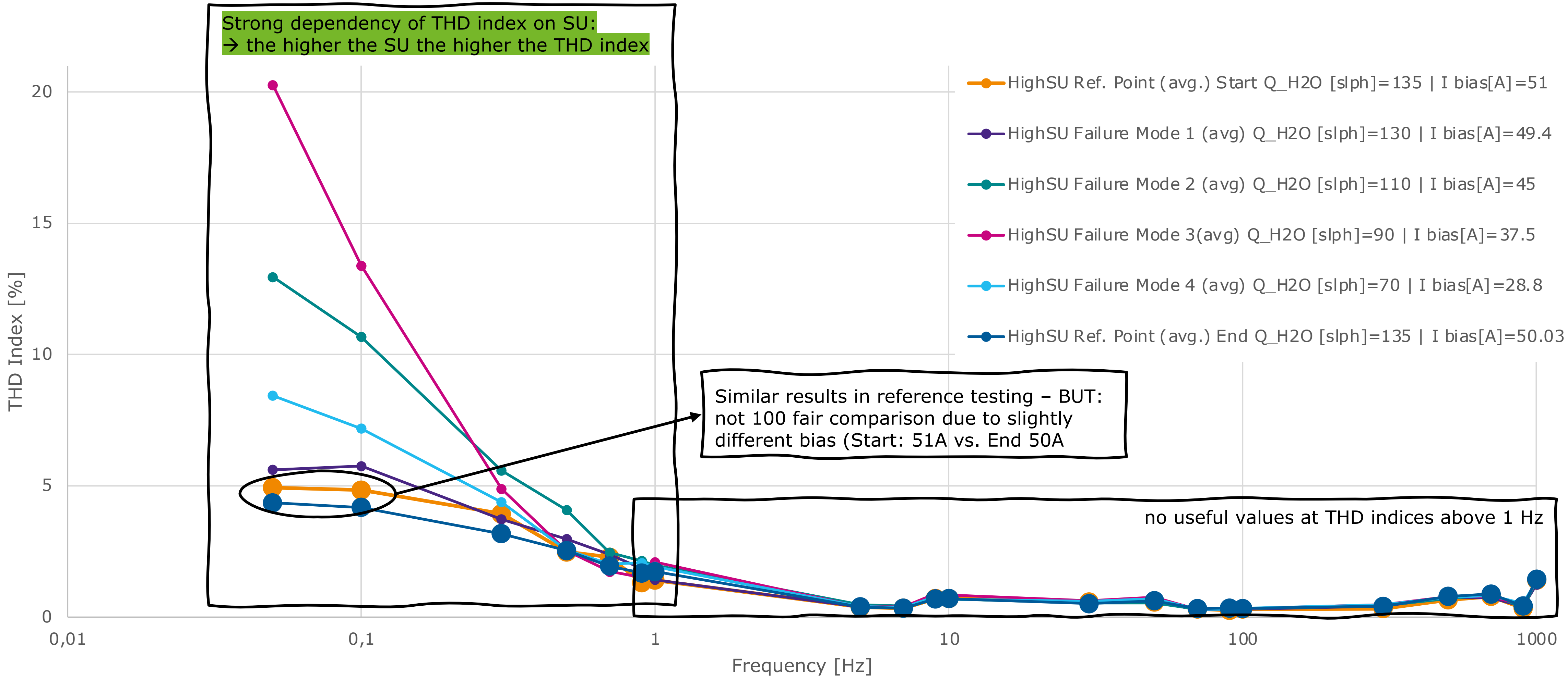
- CAE partly executed inlet H_2 starvation with only 97/3 and 100/0 water-hydrogen inlet ratio drops
- Excitation amplitudes were at 8% of the bias (bigger then what CAE applied) and multiple more excitation frequencies were applied in the frequencies range
- Large percentage of recorded corrupted (ripples, constant parts, not long enough) → high effort for postprocessing needed



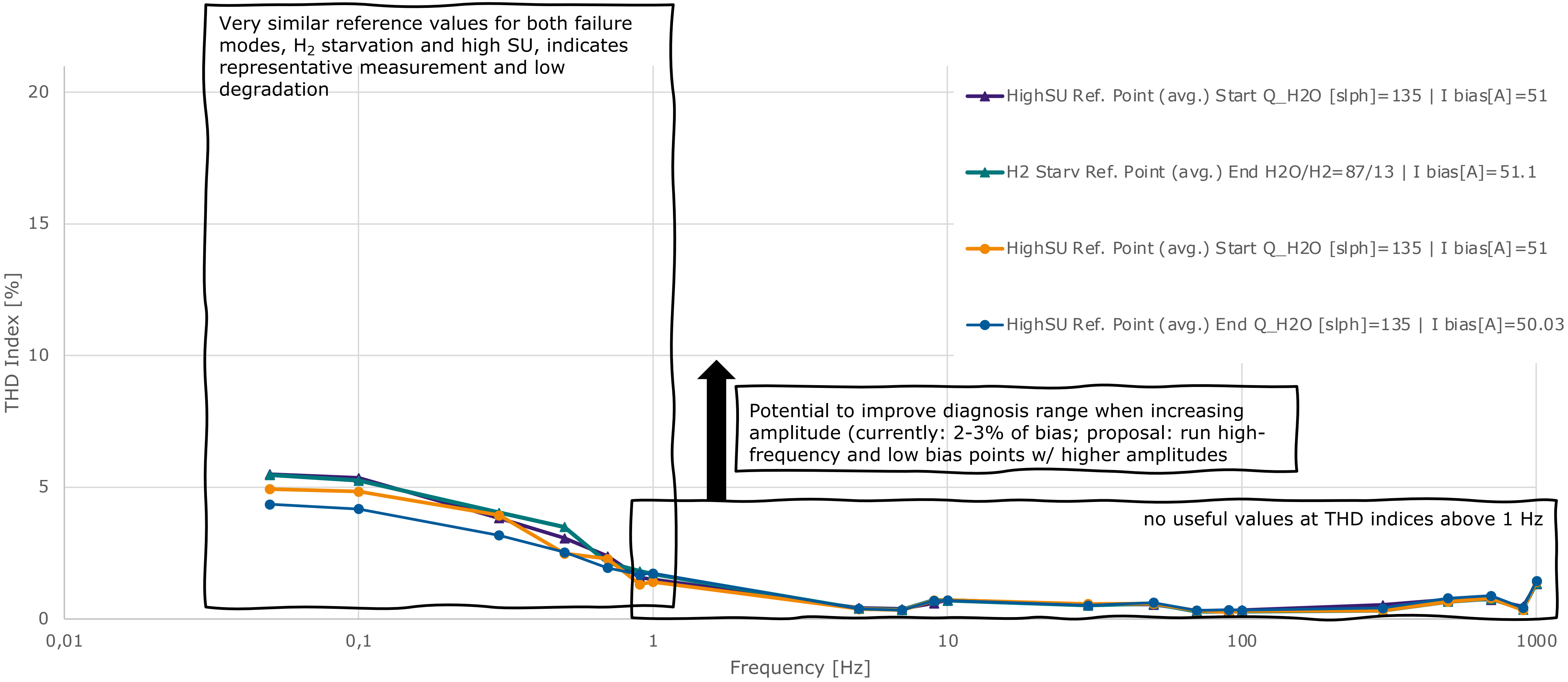
CEA H_2 starvation testing – Results



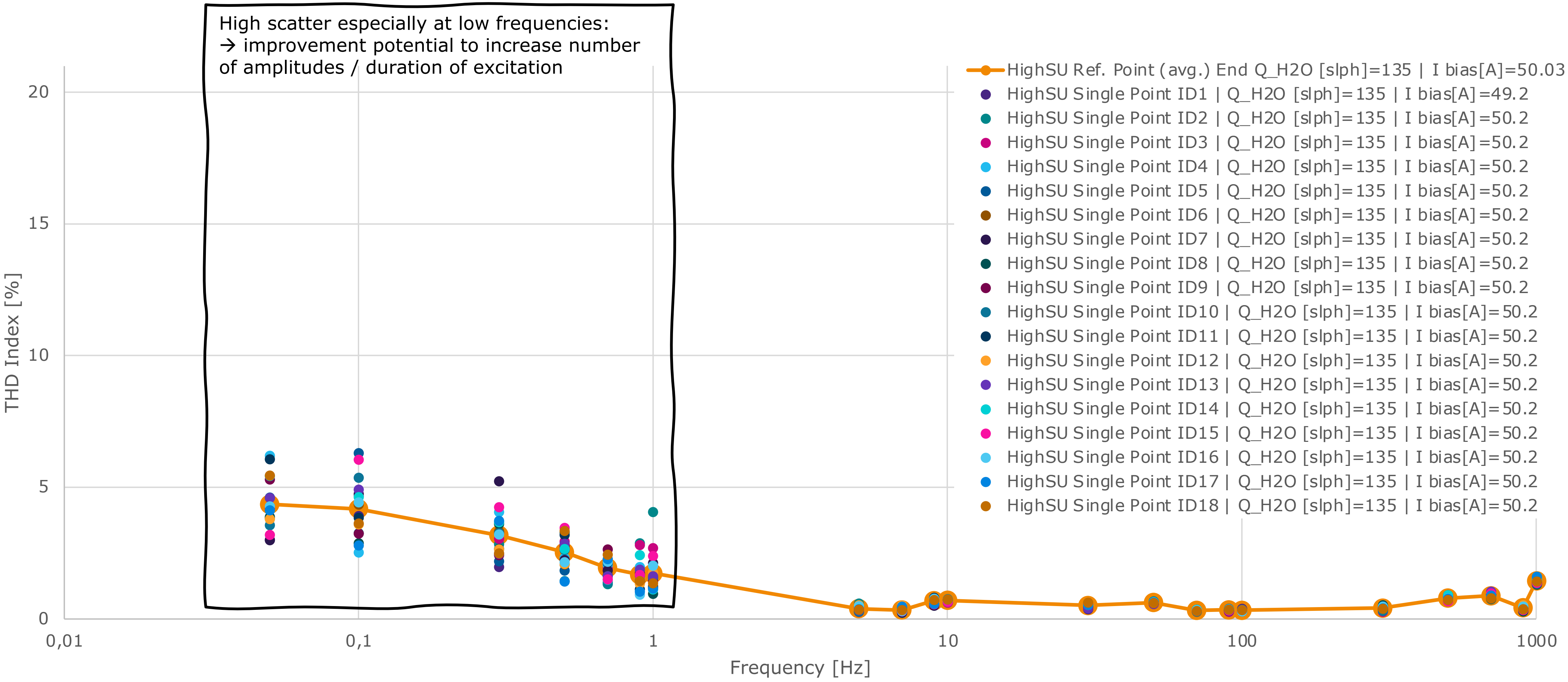
CEA high steam conversion testing – Results



Comparison of reference points – start and end of test



Comparison of references (avg.) w/ individual measurements



Conclusion

- THD analysis algorithm available and applicable
- Due to lack of data, a clear diagnosis strategy cannot be verified yet
- Involvement in further testing highly appreciated
  - clarification from AVL side how X-ion can be used within full stack testing
  - updated sinusoidal perturbation sequence to be applied in further testing
    - longer duration at lower frequencies (to decrease variance of single test points)
    - increase of amplitudes especially at low bias (and high frequencies)
    - decrease of frequency breaking points at high frequency levels (low information content expected)

Most important: More test data required!

Frequency [Hz]	Duration of the excitation [s]
0.05	100.0
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0.7	7.1424
0.9	5.5552
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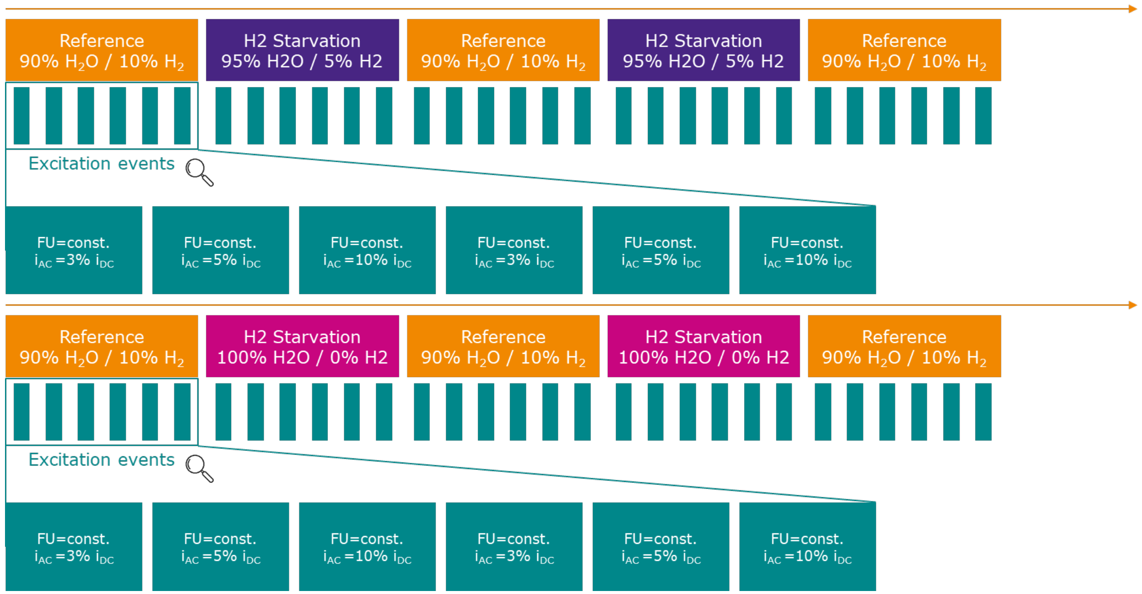
Range currently tested

Most representative range but high scatter → increase of duration (?)

Potential range w/ increased amplitudes



Thank you

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