

Self-consistent time series tracking for phase difference and improved density profile reconstruction scheme on the KSTAR reflectometer

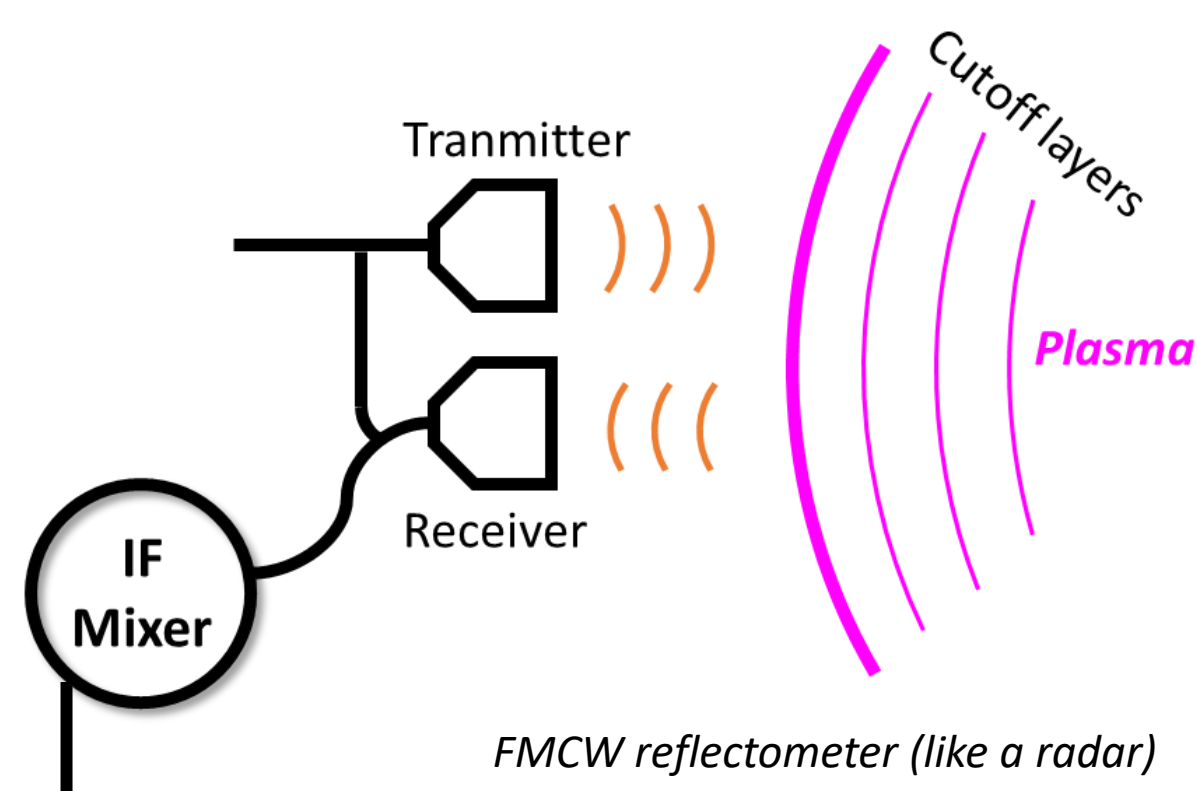
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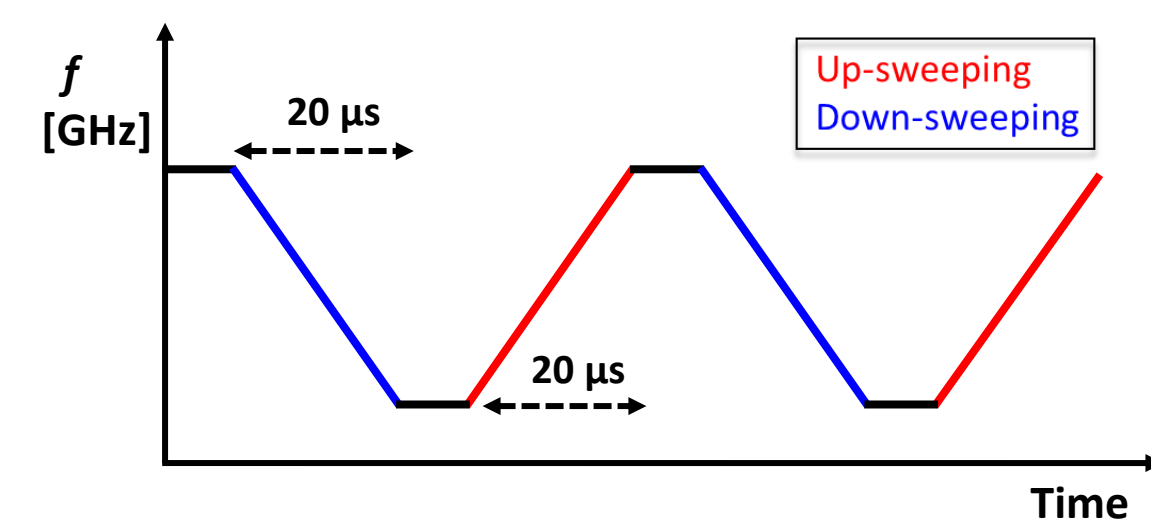
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Introduction

KSTAR FMCW reflectometer (frequency-modulated continuous wave) for density profile measurement

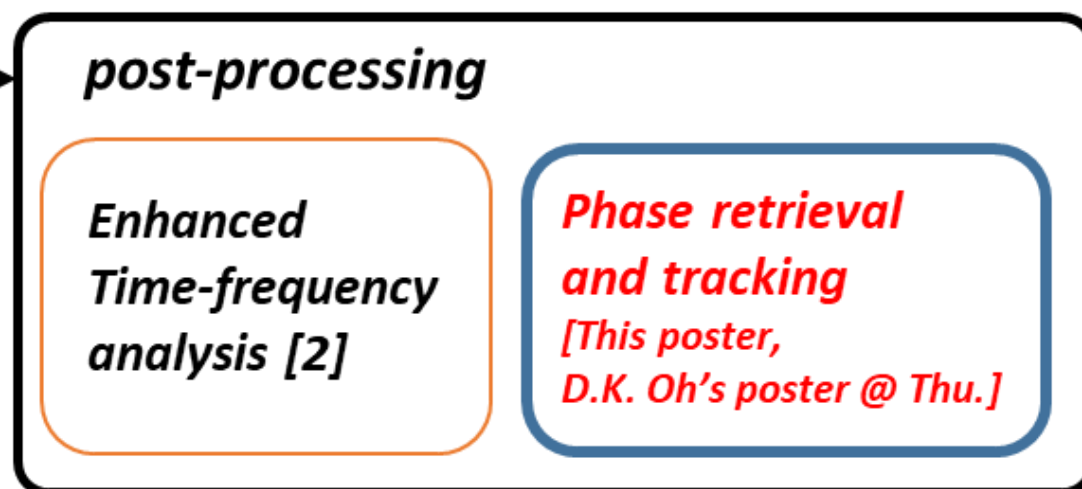


Frequency modulation



- From each plasma cutoff layer, continuous waves with swept frequency are reflected, and the phase difference (detected at IF mixer) occurs.
- KSTAR X-mode reflectometer (3 sweeping bands) can covers from edge to core plasma.

Q-band: 32-48 GHz, V-band: 48-72 GHz, and W-band: 72-108 GHz

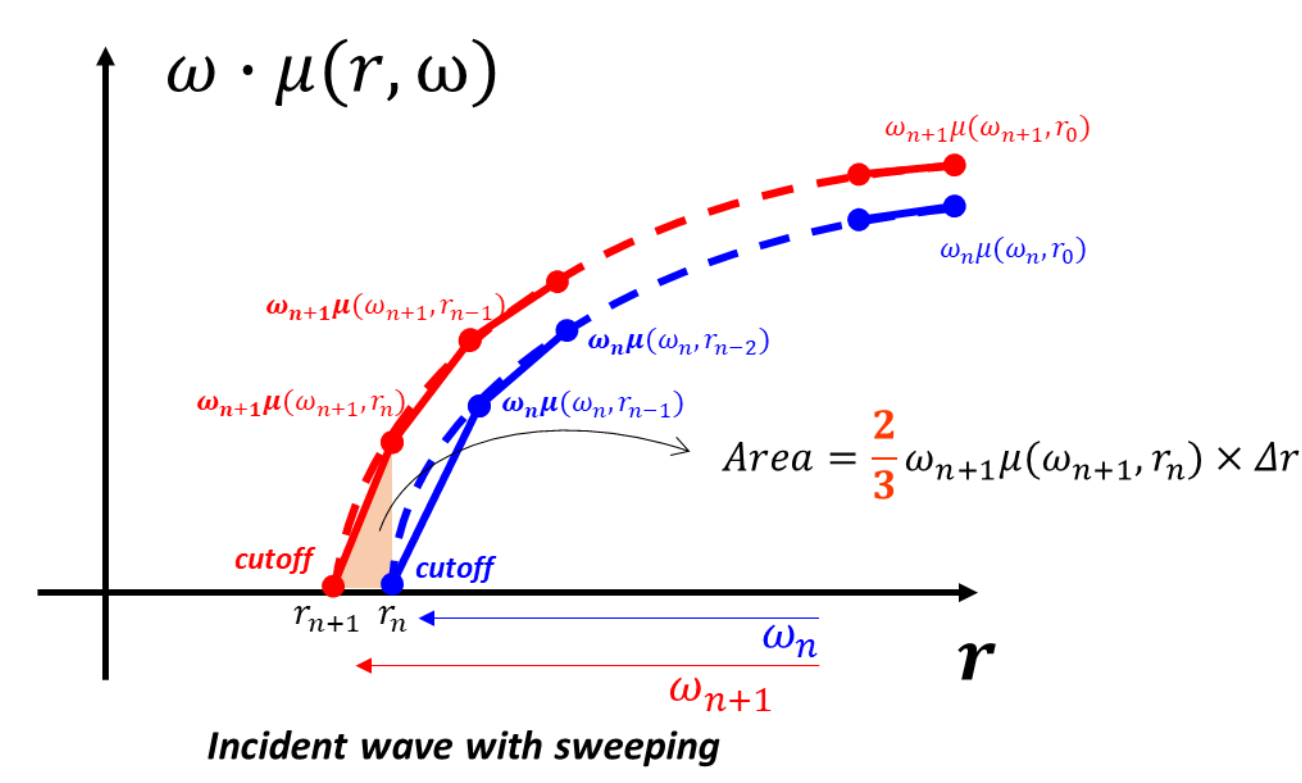


- However, in real-experiments, dedicated post-processing techniques are necessary.

Density distribution

(Inversion algorithm)

Bottollier-Curtet algorithm [1]



$$\text{The refractive index } \mu(r, \omega) = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2 \frac{(\omega^2 - \omega_p^2)}{(\omega^2 - \omega_p^2 - \omega_c^2)}}$$

$$\text{The phase difference } \Delta\phi = \frac{\omega}{c} \int_{r_0}^{r_0 + \Delta r} \mu dr$$

$$\omega_p^2 = \frac{e^2 n_e(r)}{m_e \epsilon_0}, \quad \omega_c = \frac{eB(r)}{m_e}$$

Problems in raw signals

- High noise (but density fluctuation actually happen!)
- Multi-component signal (left hand cutoff, clutters, etc.)
- AM-FM (Amplitude modulated, frequency modulated)
- ZC (Zero-crossing)

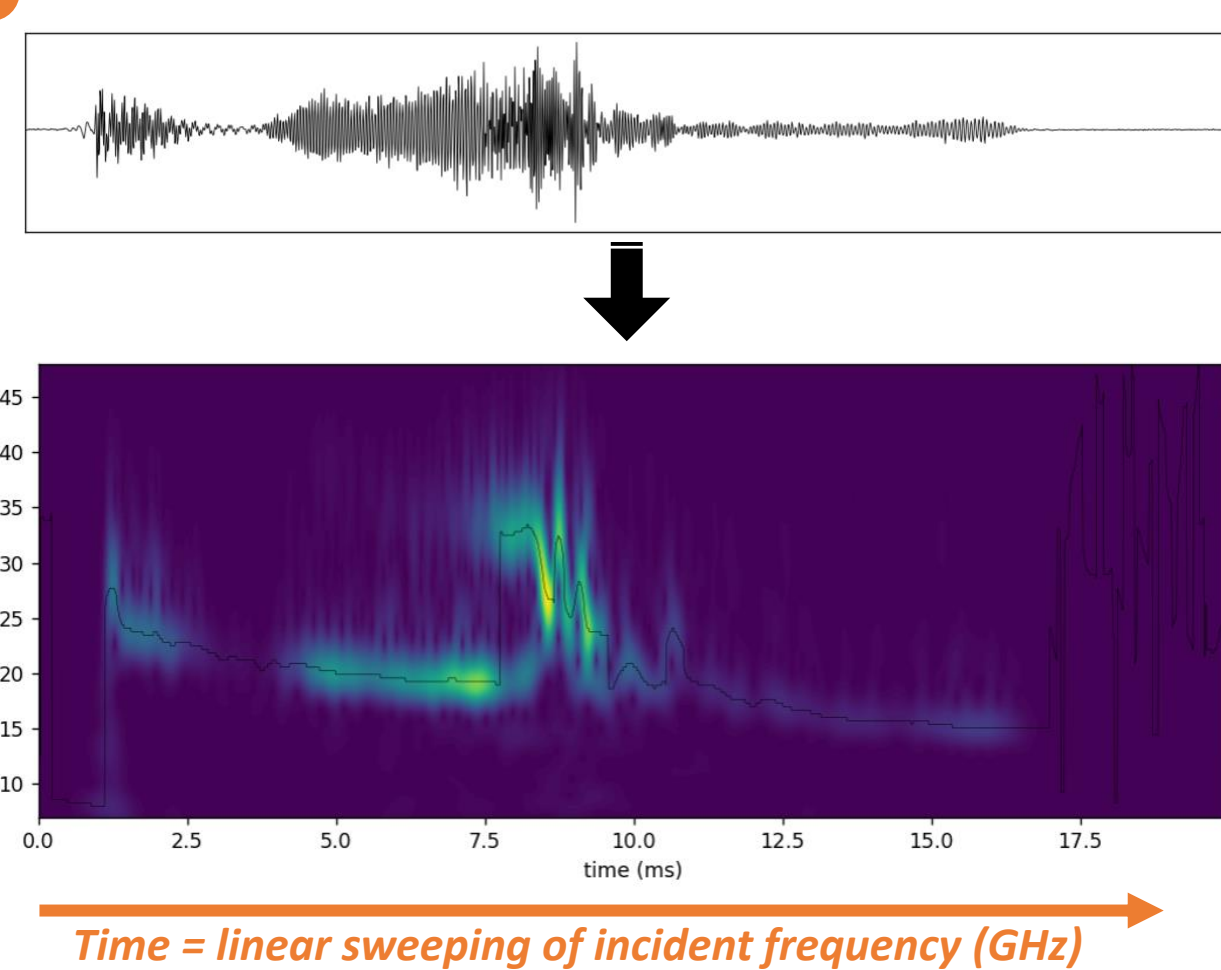
→ Signal processing and ML (possibly) techniques

Time-Frequency Analysis

Wavelet Transform (WT) [3]

- For the accurate analysis of instantaneous frequency (IF), wavelet transform is introduced.
- Wavelet transform is better for analyzing temporarily localized frequency variations (cf. STFT) with a fast sampling rate (100GHz)

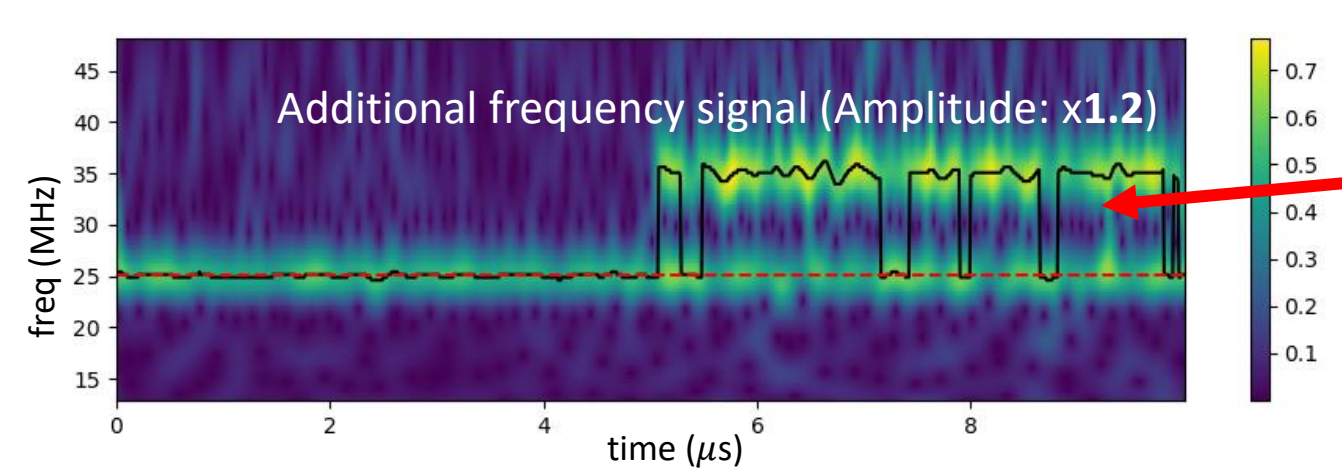
$$z(t, f) = Ae^{i\phi} \text{ (complex WT, CWT)}$$



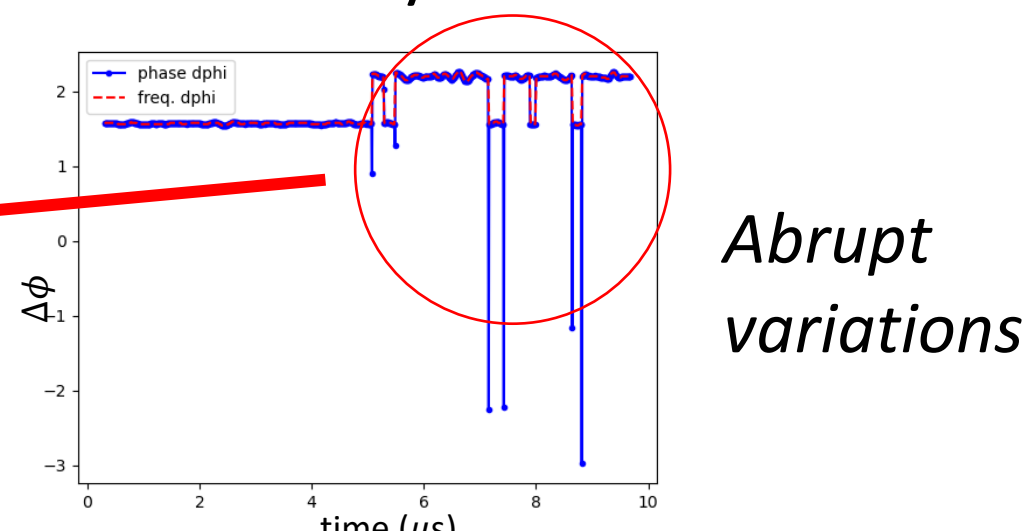
Self-consistent phase difference

$$1) \Delta\phi_P \equiv \arg(z_t^* z_{t+1})$$

$$2) \Delta\phi_F \equiv \frac{2\pi(f_t + f_{t+1})}{2} \Delta t, \quad \omega = 2\pi f = \frac{d\phi}{dt}$$



- Given the tracked path in a CWT, one can calculate the phase difference in two ways.



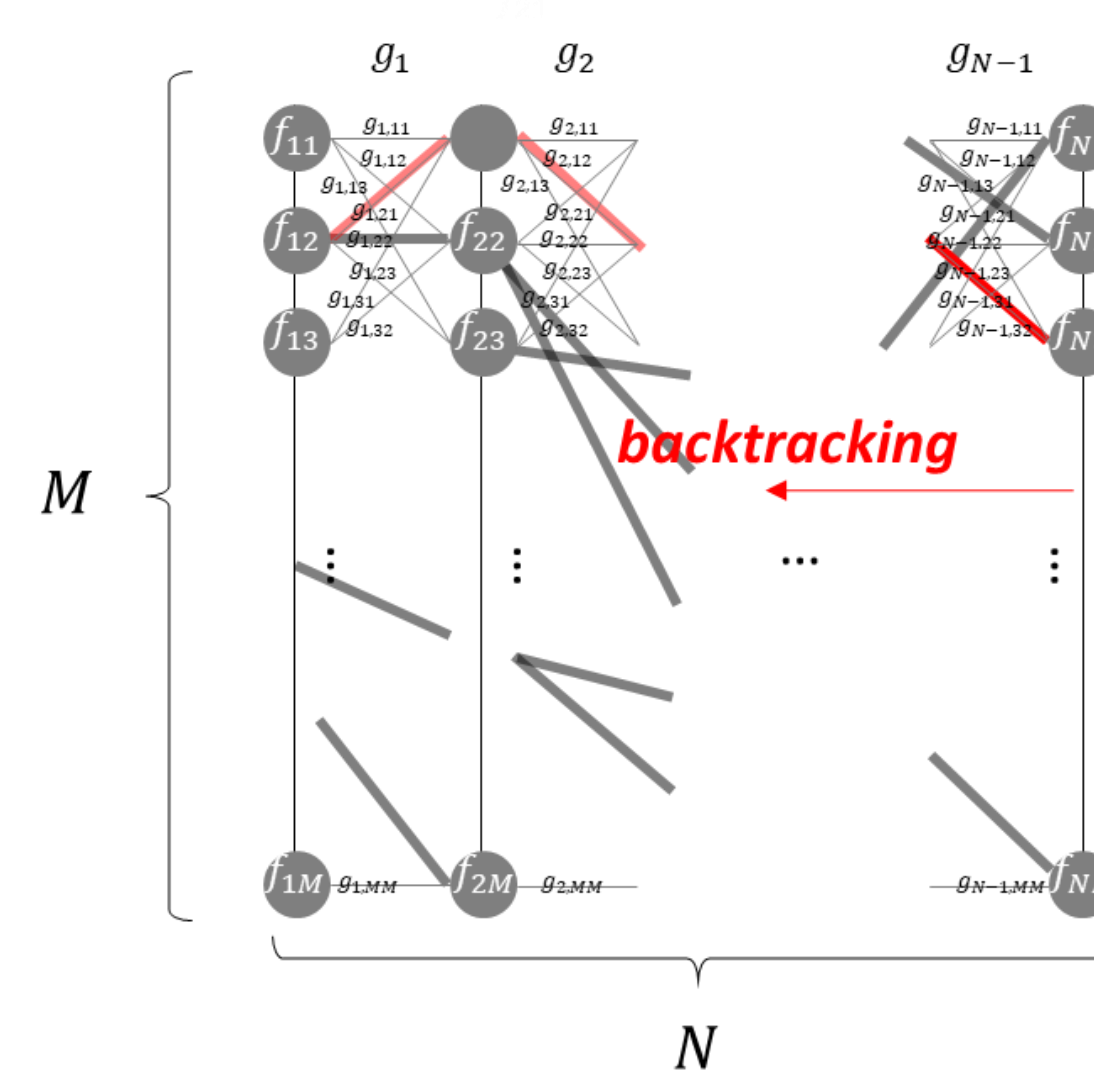
Method

Viterbi algorithm [4]

$$\text{argmax}_{y \in S} p(y_1, y_2 \dots y_N)$$

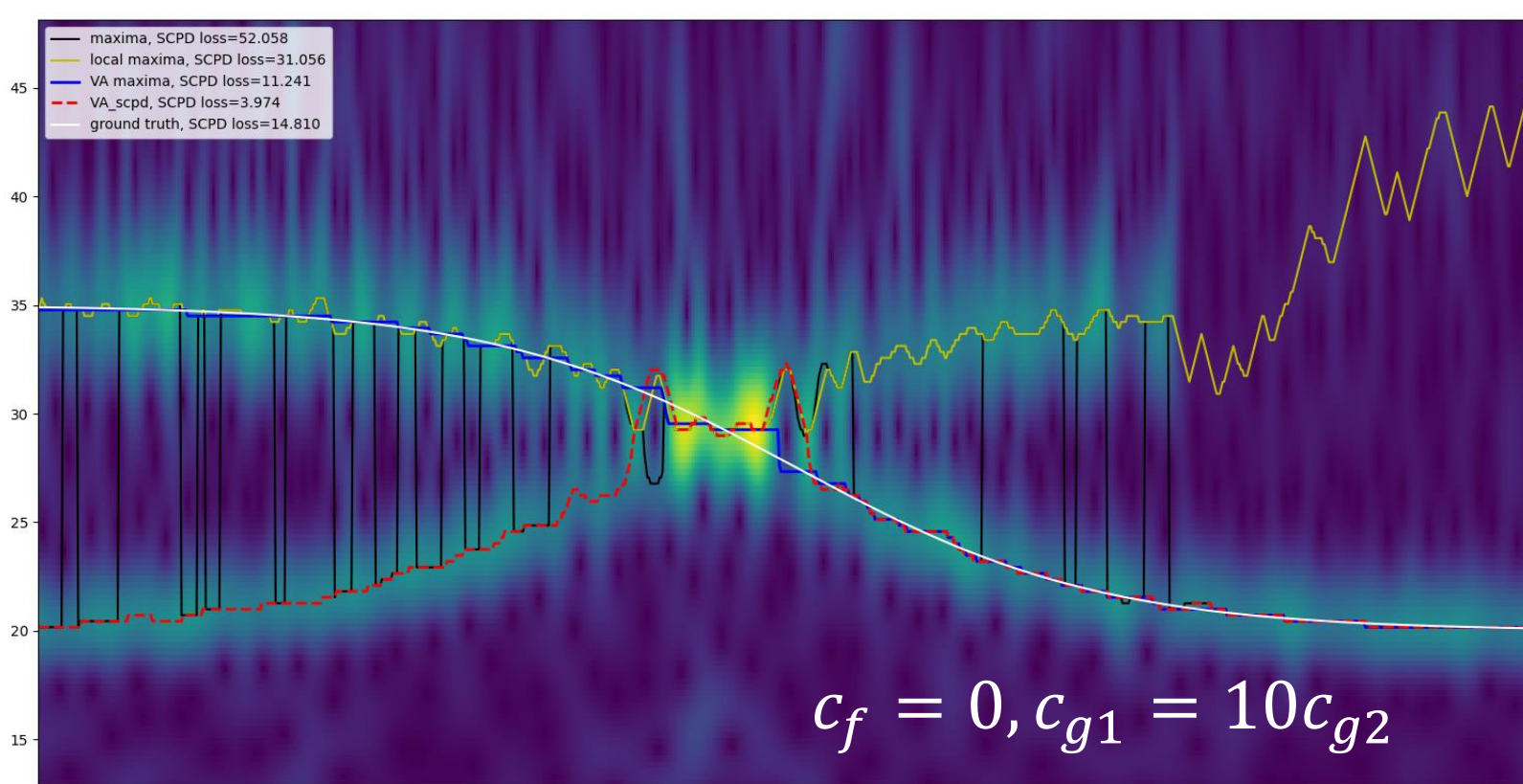
Loss (or penalty) ~ log-probability

$$\text{argmin}_{y \in S} L(y_1, y_2 \dots y_N)$$

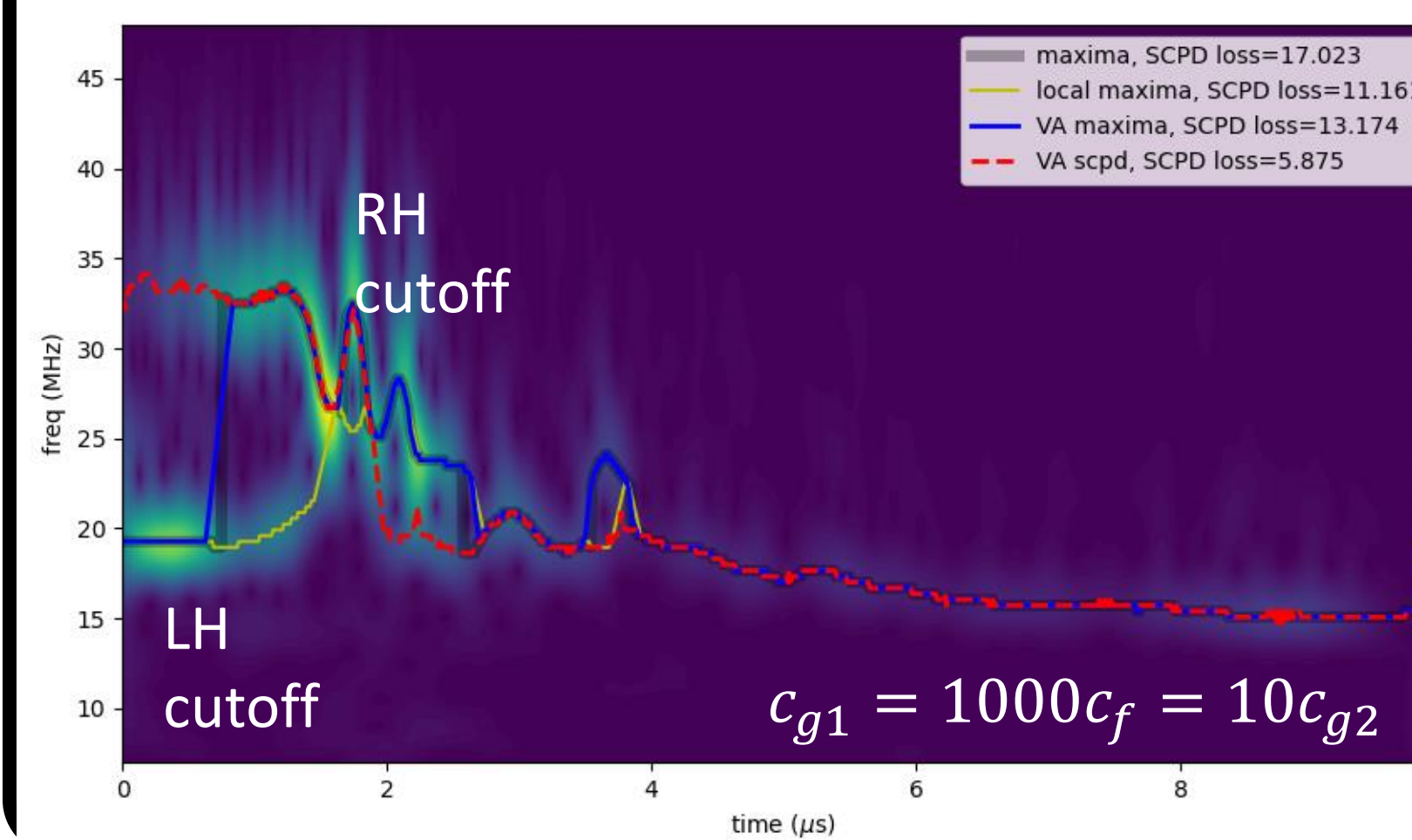


Results

- Synthetic data



- Real FMCW reflectometer data



Sequential decoding

- The Viterbi algorithm (VA) estimates the maximum likelihood of the state sequence of the Markov model.

- Variants of VA are commonly used in communications, speech recognition, part-of-speech tagging, and also IF tracking of micro-doppler signals [5,6].

$$L(y_1, y_2 \dots y_N) = c_{g_1} \sum_{n=0}^{N-1} |\Delta\phi_p(y_n, y_{n+1}) - \Delta\phi_f(y_n, y_{n+1})| + c_f \sum_{n=0}^{N-1} f(y_n) + c_{g_2} \sum_{n=0}^{N-1} |y_n - y_{n+1}|$$

Auto-term (emission): $f(N \times M)$

Cross-term (transition): $g(N-1 \times M \times M)$

- Synthetic signals have:
 - Gaussian white noises
 - random chirping
 - double components (AM) with a crossing

- Even with very low SNR data, VA recovered well-connected lines without consideration of magnitude, but remains crossing region and unsplit components.

- In real Q-band signals, it reconstructed more likely signals after pre-parameter optimization.

- Under VA contexts, the advance of sequence tracking is expected by more physically explainable consideration. e.g. additional penalty terms

Extension to ML techniques (planned)

- Combination with the Bayesian mixture model (D.K. Oh@ Thu, poster) can suppress the fault in crossing regions and overlapped multi-components.
- Sequential machine learning models (RNN or LSTM) can be applied if there exist enough training datasets.
- Seq2seq and Attention have also applicability with full time-frequency domain information.
- In the penalty used here, density reconstruction is more automatic and faster by reinforcement learning without supervised density profiles.

Conclusion

- In tokamak density profile diagnostics, a sequential tracking method is developed for more probable time-frequency analysis.
- Viterbi algorithm with self-consistency of phase information made good paths in high noise signals.
- It is possible to extend to ML techniques for enhancing the integrity of the measurement.

Bibliography

- H. Bottollier-Curtet and G. Ichtchenko, Rev. Sci. Instrum., 58 539 (1987)
- S.-H. Seo and K. D. Lee, Rev. Sci. Instrum., 83, 10E342 (2012)
- C. Torrence and G. Compo, Bull. Am. Meteorol. Soc. 79(1), 61-78 (1998)
- G. D. Forney, Proc. IEEE, 61(3), 268-278 (1973)
- I. Djurović and Lj. Stanković, Signal Processing 84, 631-643 (2004).
- P. Li et al., Circuits Syst. Signal Process 39, 3105-3124 (2020)
- S.-H. Seo, Plasma Phys. Control. Fusion 65 015010 (2023)
- C. M. Bishop, Pattern Recognition and Machine Learning, Springer (2006)