Improvement and validation of swept density reflectometry in IDA at ASDEX Upgrade

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Overview

From the title two main points:

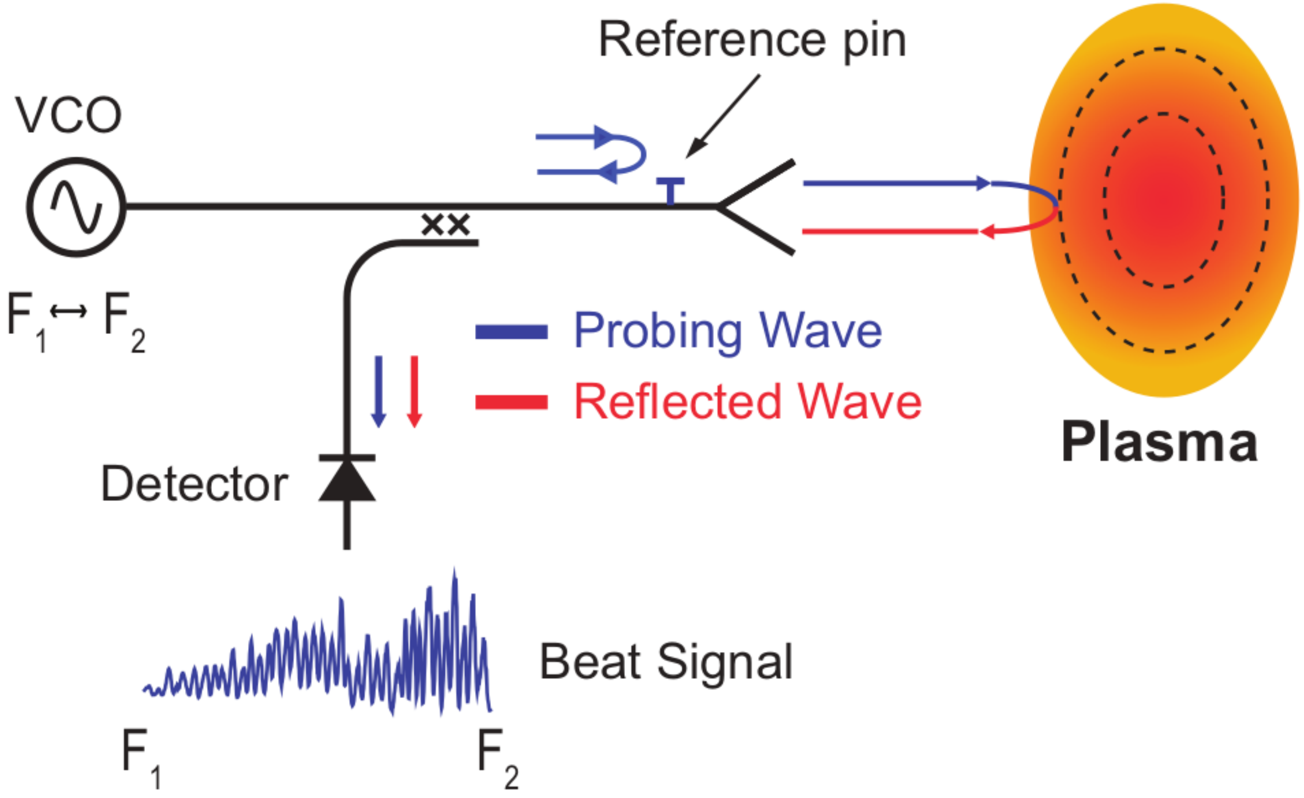
- **Improvements:**
  - **Forward Model**
  - Pre-processing of Raw-Data
  - Equilibrium mapping
- **Validation:**
  - **Not in a mathematical sense**
  - **Does it corroborate other diagnostics? Do we get a coherent result?**
  - Effect of turbulence, geometry, … physics missing?

Swept Density Profile Reflectometry (O-Mode)

Basis:

- Microwave chirp ~ 10-100 GHz
- Reflected at cut-off density
- Overlaid with reference signal
- Beating, due to changing phase delay
- Low-Pass Filter
- Sampling at 40 MHz

- O-Mode only (so far)



Reflectometry – Interferometer with many LOS

Reflectometry is interferometry, but with variable path lengths

- Interferometry

  integrate refractive index along LOS → collected Phase

$$\int_{x=0}^{x=L} \eta(x)\, dx \qquad\qquad \phi \implies L\langle n\rangle$$

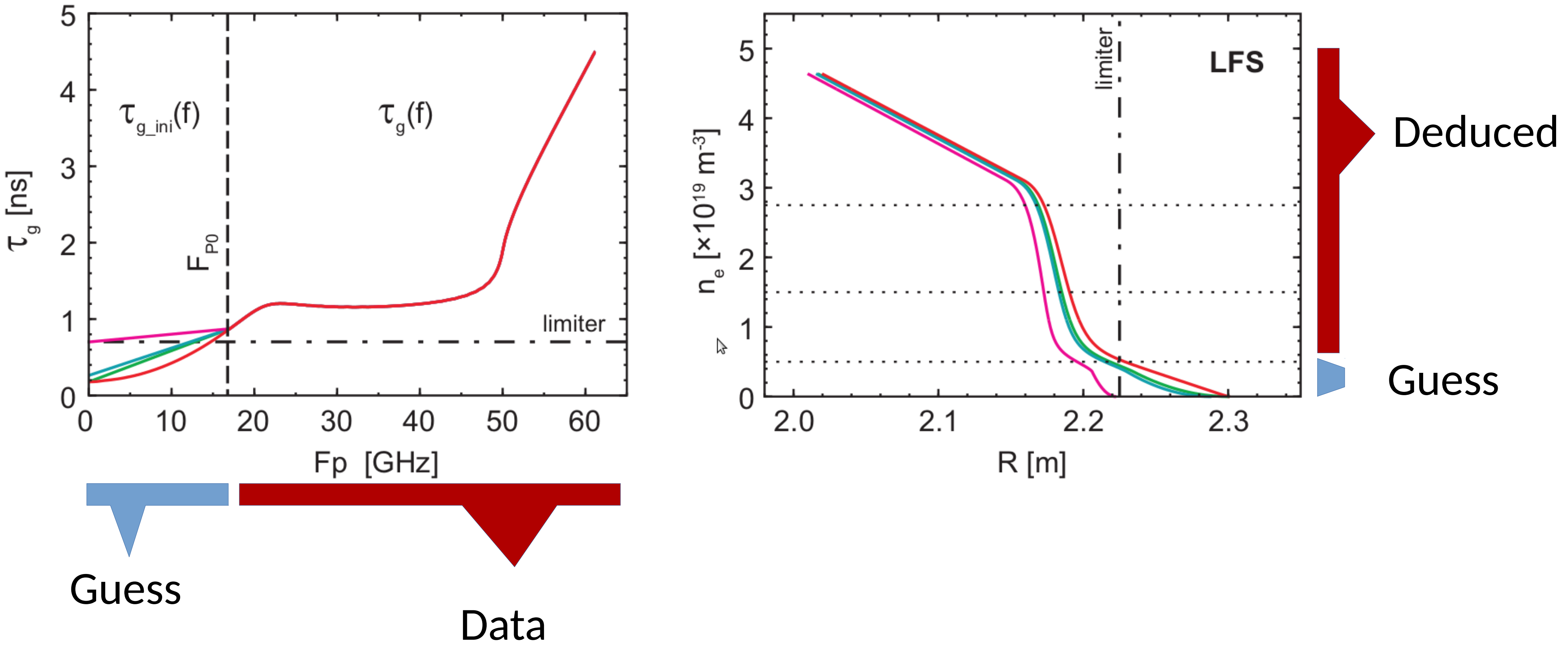
- Reflectometry: integrate inverse refractive index → group delay (not time of flight)

$$\int_{x=0}^{x=L(\omega,n(x))} \frac{1}{\eta(x)} dx \qquad\qquad \tau_g \propto \frac{\partial\phi}{\partial\omega_P} \implies L(\omega, n(x))\langle 1/n\rangle$$

Reflectometry – Initialisation

Group Delays are a result of integration → non-local effects

Figure from J Santos Thesis (2008)

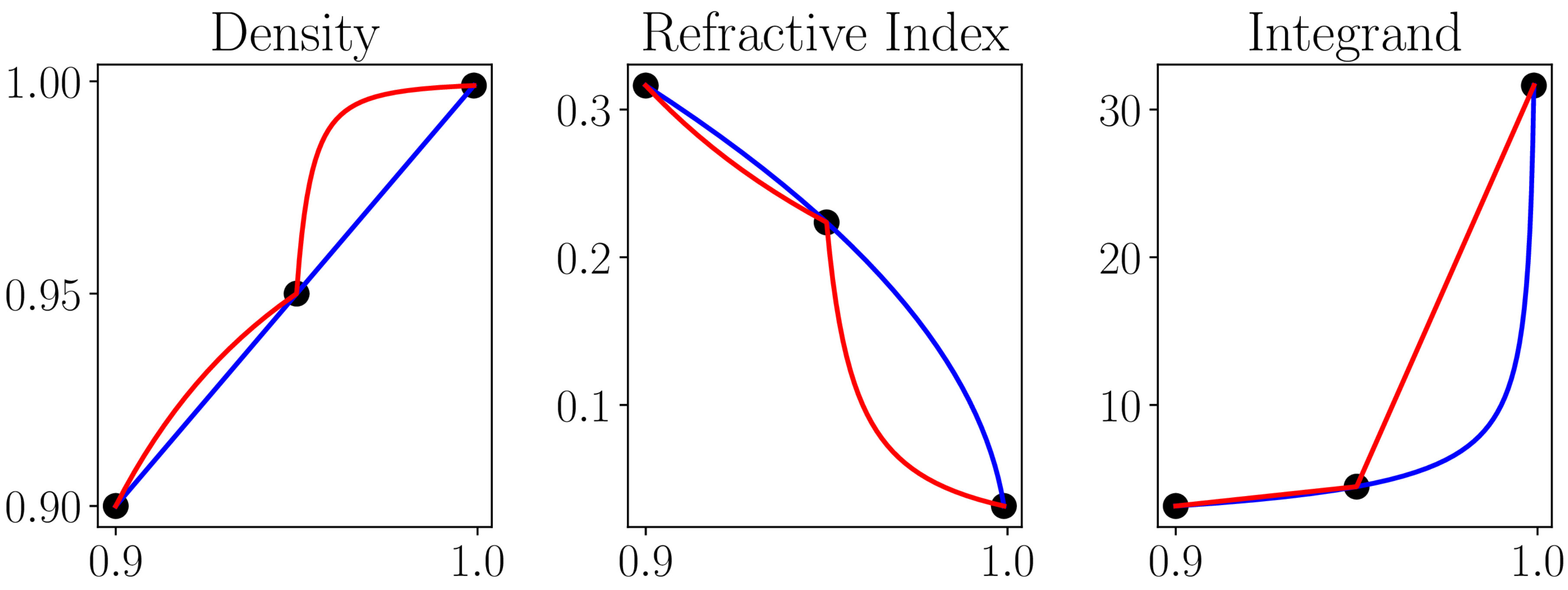


Group Delay – Forward Model

- Example: n / n_cutoff = [0.9, 0.95, 0.999]
- Trapezoidal rule treats $1\,/\,\eta$ as linear
  Leads to diverging integral at cut-off
- Solve piece wise with linear n
  Does not diverge, exact for linear n

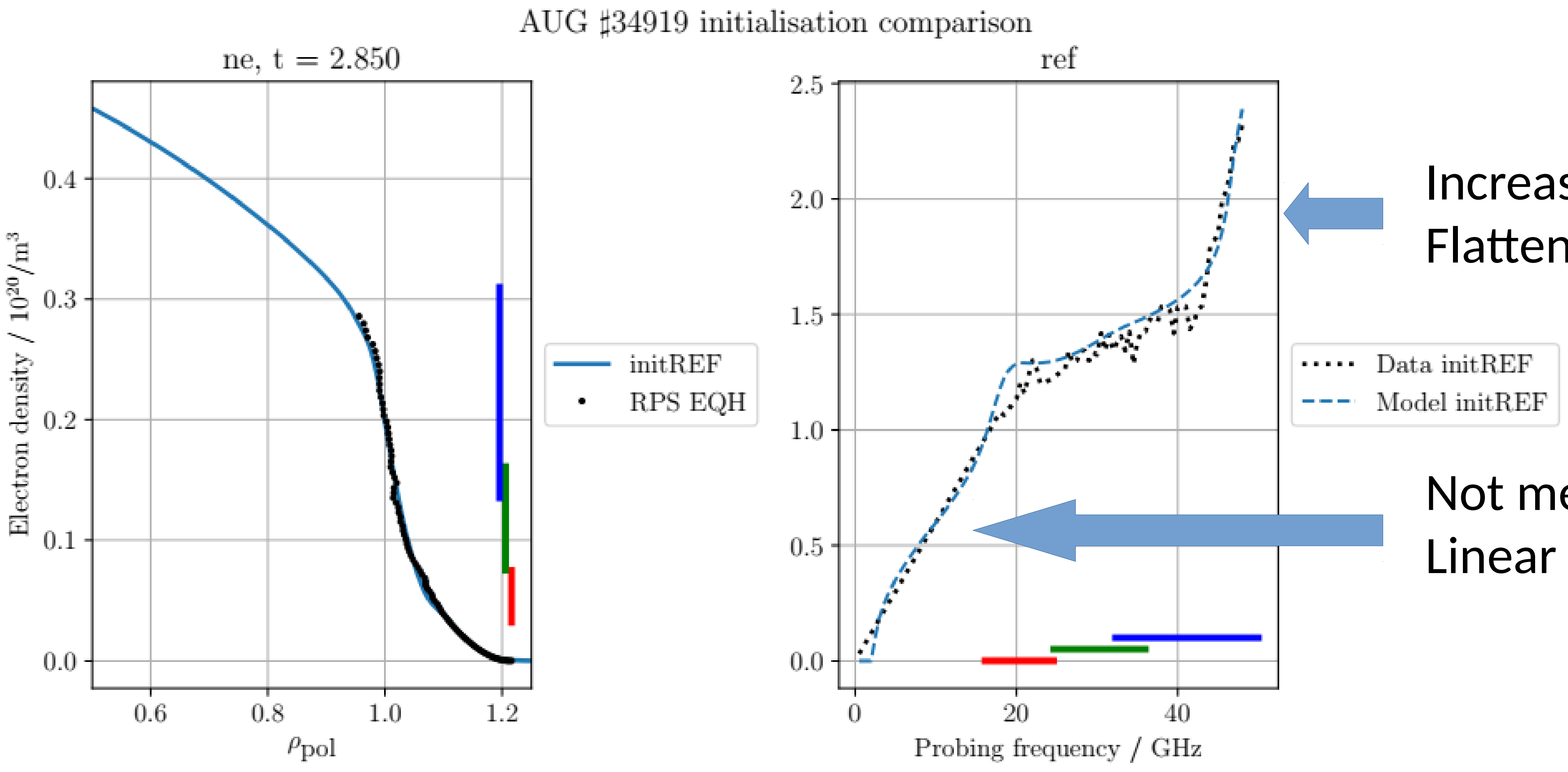
$$\int_a^b \frac{1}{\eta(x)}\mathrm{d}x \approx (b-a)\left(\frac{1}{\eta_b}+\frac{1}{\eta_a}\right)/2$$

$$\int_a^b \frac{1}{\sqrt{1-n(x)/n_c}}\mathrm{d}x = (b-a)\cdot\frac{2}{\eta_b+\eta_a}$$



Reflectometry – Recent result from AUG

Only Reflectometry in SOL – including linear interpolation < 18Ghz => as classic/Abel



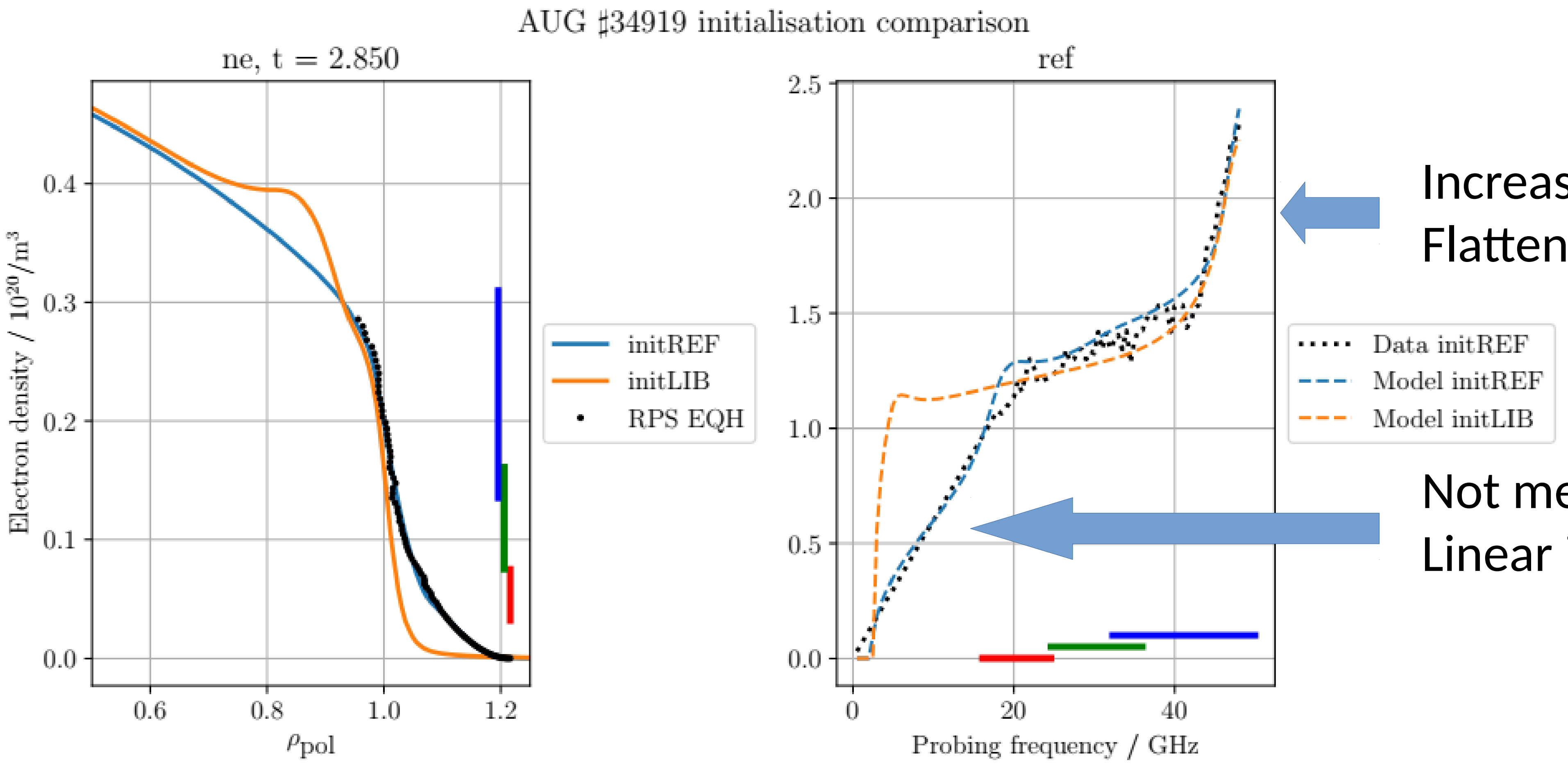
Increase in GD
Flattening in n

Not measured
Linear interp.

Measurement range in f and n: K-Band - Ka-Band - Q-Band

Reflectometry – Recent result from AUG

Reflectometry >= 18Ghz plus other diagnostics => 20-50 GHz agree well



Increase in GD
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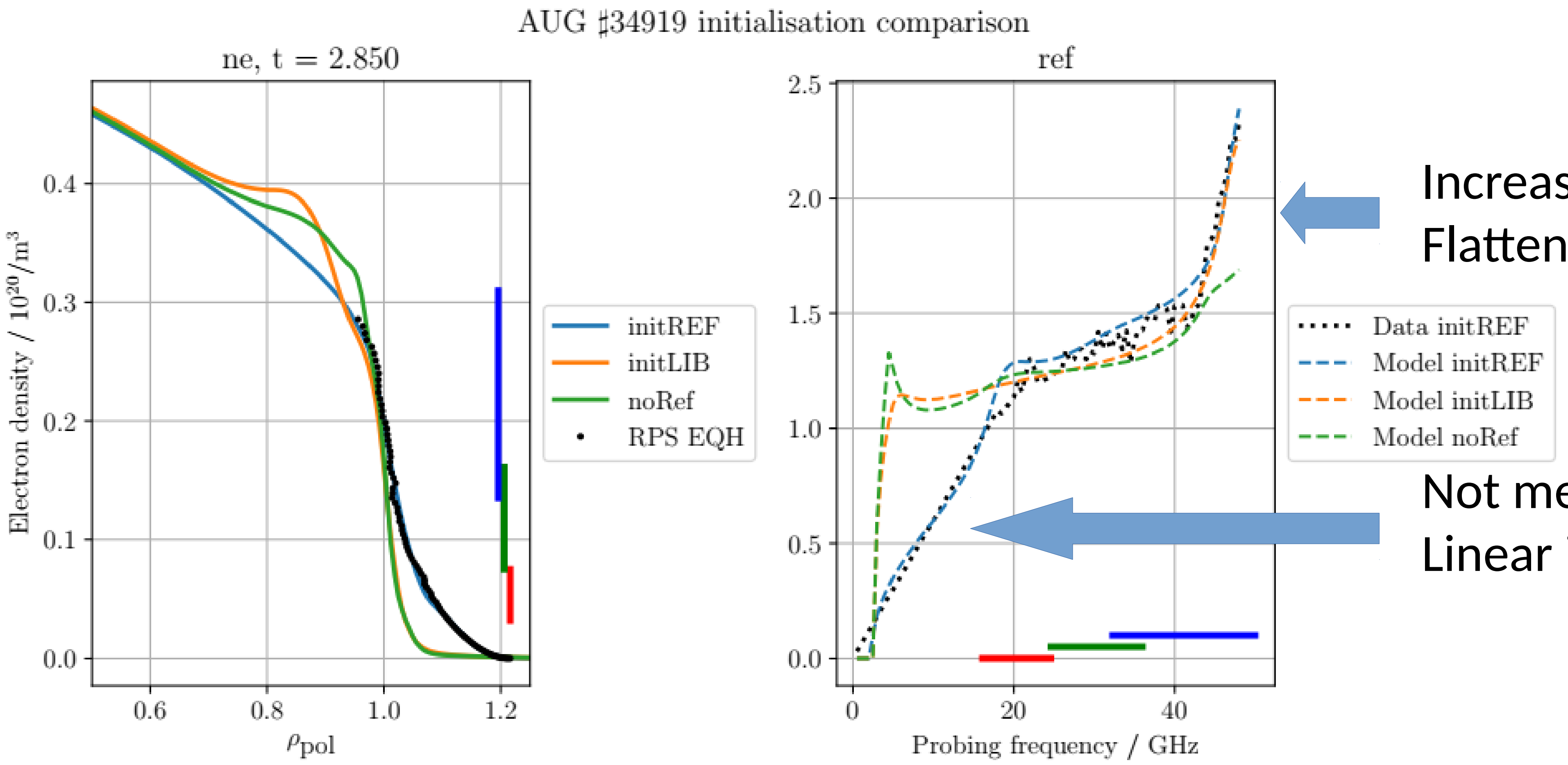
Reflectometry – Recent result from AUG

No Reflectometry => different behaviour at pedestal top >= 40GHz



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Why validation in IDA?

Typical sources of discrepancy:	Reflectometry
• Offset/Vibrations in absolute coordinates	WG calibrated
• Offset/Drift in intensity calibration	------
• Invalid model assumptions	[WKB, turbulence, 1D]

- Assuming rotationally symmetric profiles – does break down in some cases
  Not enough diagnostics to describe the SOL fully in 2D
  Variation on short spatial scales, e.g. wall elements

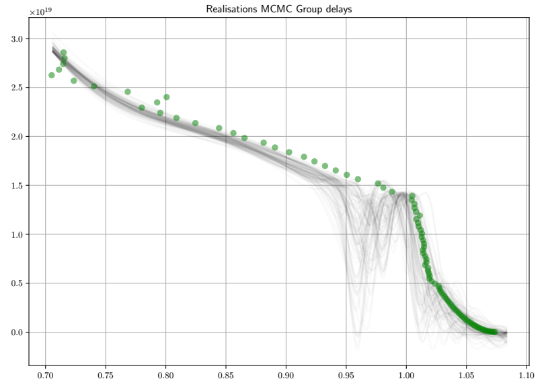
Solutions:

- More diagnostics
- Comparison to Modelling Codes (SOLPS, EMC3-EIRENE, **ASTRA**)
- Bayes: Estimate uncertain parameters like offsets

Summary

- Profile Reflectometry at AUG provides useful information
- Bayesian Treatment...
  - does not care about Initialisation
  - or “gaps” in the sweep
  - and is outlier resistant
- **Proper** forward model is used (numerically stable, smooth change with input...)
- Disagreement between several diagnostics motivates further work on all diagnostics

Outlook for Reflectometry



- Analyse non-monotonic profiles – important on HFS => HFSHD
- Improve pre-processing of raw data
  - Beating frequency with UQ
  - Properly infer chirps / frequency jumps (FFT assumes signal is sum of harmonics)
  - Use Bayesian methods to improve calibration, e.g. description of waveguide
- Quantify fluctuations within the usual time window of 1ms
  → quantify mean density with uncertainty plus fluctuation level with uncertainty

Backup – Integrated Data Analysis

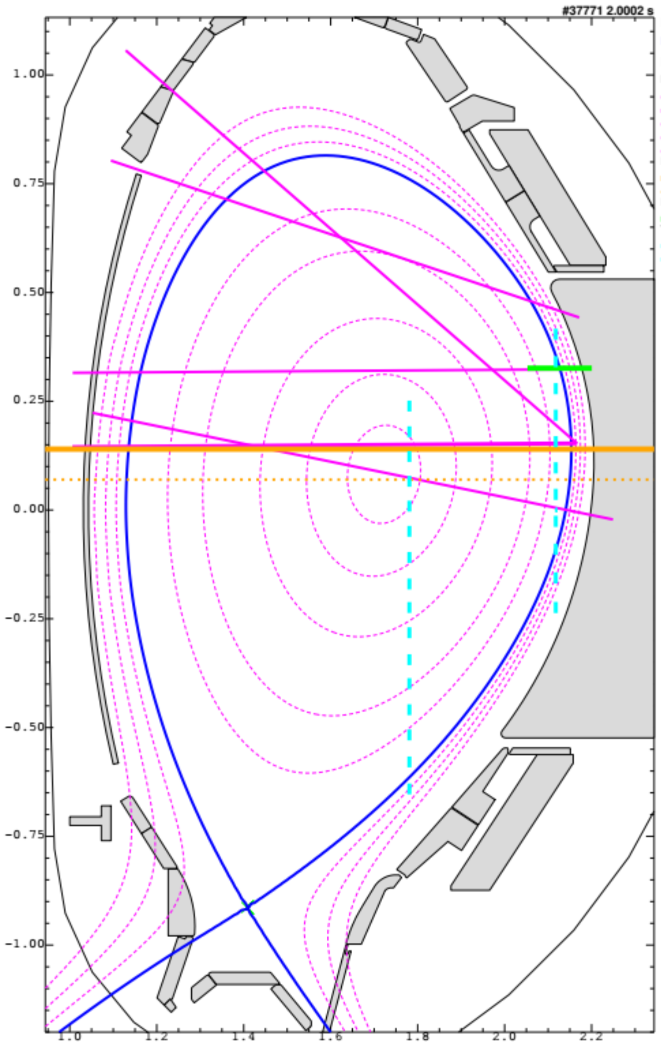
Heterogeneous Data Sources are used:

- Lithium Beam impact excitation spectroscopy (LIB) → n_e
- Interferometry (DCN) → n_e
- Thomson scattering (TS) → ne, Te
- Reflectometry (REF) → ne
- Electron cyclotron emission (ECE) → Te
- Beam emission spectroscopy → ne, Zeff
- Helium beam (HEB) → ne, Te

Why Reflectometry?

It fills gaps, e.g. when

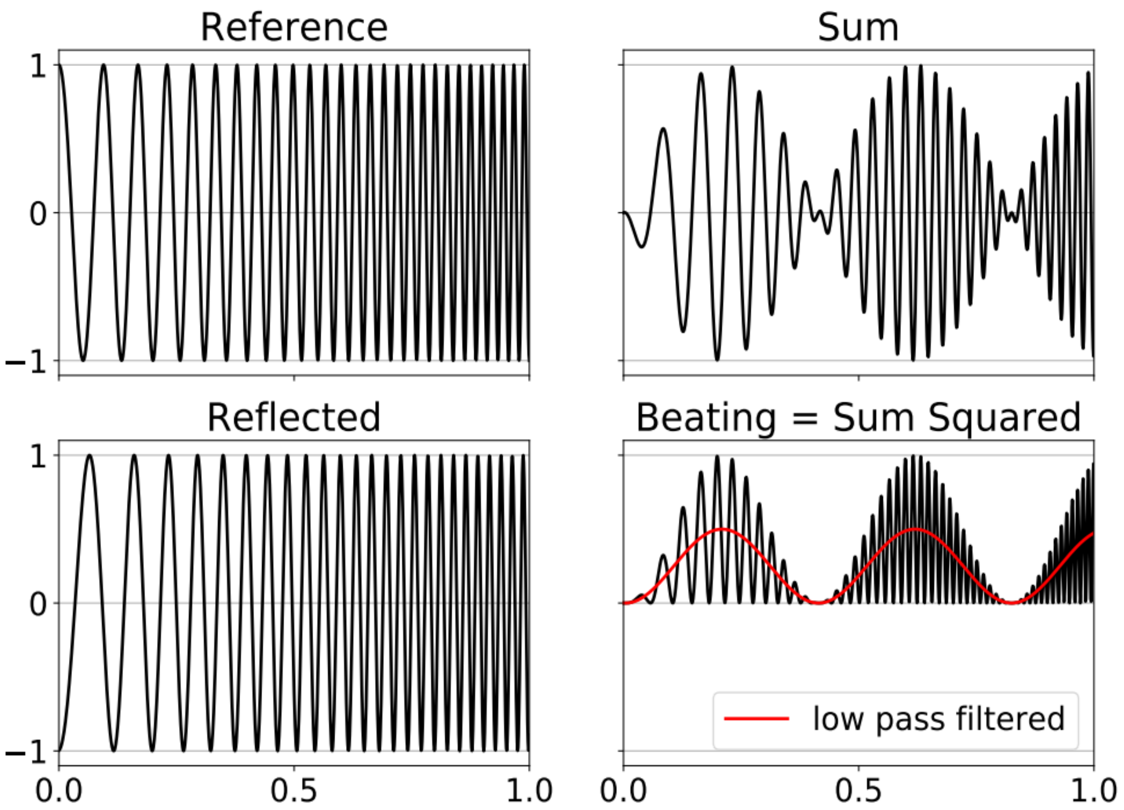
density too high for LIB or Position unfavourable for TS



Backup - Swept Density Profile Reflectometry

Classic Analysis

- Sampled signal
  → FFT for Spectrum
  → Beating Frequency
  → Group delay
- Abel inversion
  → deterministic, always gives an answer
- Relies on initialisation of profile
  = guess group delay below lowest data
- Actually returns the distance to cut-off along LOS: $r(n) \neq n(r)$



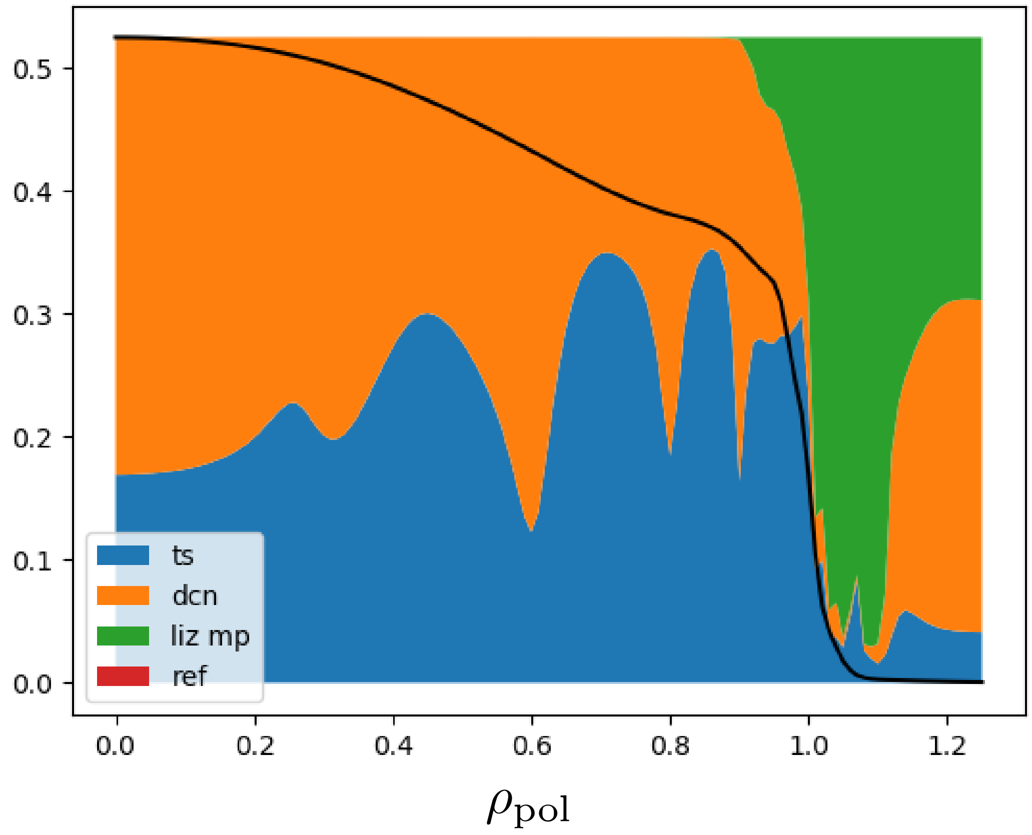
Backup – Analyse Uncertainties

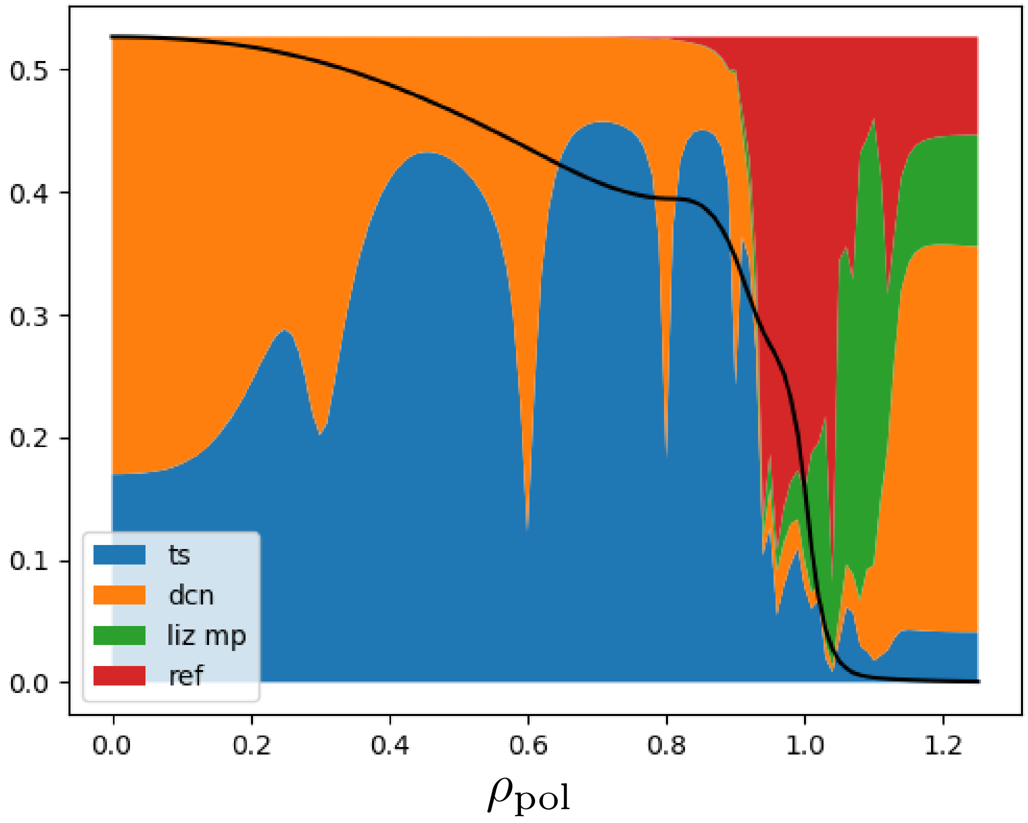
Central question: Which diagnostic informs which part of the profile?

Building on Laplace-Approximation (covariance matrix at MAP)

Relative Certainty

$$\left(\frac{\sigma_{diag}}{\sigma_{total}}\right)^{-1}$$





Backup – Group delay vs Time of Flight

- Group Delay: derivative of the phase relationship of reference and plasma-wave

$$\tau_g = \frac{\partial \phi}{\partial \omega}$$

$$\omega_b = \frac{\partial \phi}{\partial t} = \frac{\partial \phi}{\partial \omega} \cdot \frac{\partial \omega}{\partial t} = \tau_g \cdot \kappa$$

- Time of Flight: phase collected by the plasma wave – ratio, no derivative!

$$tof = \phi / \omega$$