Fast Electron Temperature Measurements Based on Langmuir Probe Current Harmonic Detection on D-IIID

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Fast Electron Temperature Measurements Based on Langmuir Probe Current Harmonic Detection on DIII–D[1] D.L. RUDAKOV, J.A. BOEDO, R.D. LEHMER, R.A. MOYER, G. GUNNER, University of California, San Diego, J.G. WATKINS, Sandia National Laboratories — A comparatively new method for the measurement of electron temperature with high spatial and temporal resolution was recently implemented on a fast reciprocating probe on the DIII–D tokamak. The method is based on detection of harmonics generated in the current spectrum of a single Langmuir probe driven by high-frequency sinusoidal voltage. In the experiment reported here, the probe was driven at 400 kHz thus allowing temperature measurements with a bandwidth of up to 200 kHz. The first (400 kHz) and the second (800 kHz) current harmonics were detected by analog circuits, while the raw probe voltage and current were recorded at high sampling rate (5 MHz) to perform digital spectral analysis. The results obtained using those two methods are compared with each other and with swept double probe data. The suitability of the harmonic technique for turbulent heat flux measurements is tested, and several options for further improvements are suggested.

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☐ Prefer Oral Session
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Special instructions: DIII-D Poster Session 2, immediately following JC Rost

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Abstract

A comparatively new method for the measurement of electron temperature with high spatial and temporal resolution was recently implemented on a fast reciprocating probe on the **D-IIID tokamak**. The method, previously used on TEXTOR, is based on detection of harmonics generated in the current spectrum of a single Langmuir probe driven by high-frequency sinusoidal voltage. In the experiment reported here the probe was driven at 400 kHz thus allowing **temperature measurements with a bandwidth of up to 200 kHz**. The first (400kHz) and the second (800 kHz) currenmt harmonics were detected by analog circuits, while the raw probe voltage and current were recorded at high sampling rate (5 MHz) to perform digital spectral analysis. The results obtained using those two methods are compared with each other and with swept double probe data. The suitability of the harmonic technique for **turbulent heat flux measurements** is tested, and several options for further improvements are suggested.

Motivation for Fast Edge T_e Measurements in DIII-D

Fast measurements of the edge electron temperature are needed to:

- Measure the turbulent heat flux in the boundary of DIII-D in L and H mode
- Answer the questions:
  - is the H-mode transport barrier primarily a particle convection barrier, or heat conduction barrier?
  - is edge heat transport dominated by electrostatic turbulence as particle transport is?
- Evaluate errors in turbulent particle flux measurements due to neglecting T_e fluctuations
- Obtain time-resolved RMS amplitudes, cross-phases, particle and heat fluxes, to compare with predictions of analytic theory and numerical simulations
- Study transient phenomena such as ELMs, dithering L-H transitions, etc.

$\tilde{T}_e$ Measurements Are Needed to Calculate Turbulent Particle and Heat Fluxes

Particle Flux: $$\Gamma_r^{ES} = \frac{1}{B_\varphi}\left\langle \tilde{n}\tilde{E}_\theta \right\rangle$$

$\tilde{E}_\theta = -\nabla_\theta \tilde{\varphi}_p$ usually estimated as $\tilde{E}_\theta \approx -\nabla_\theta \tilde{\varphi}_\varphi$

However, $\tilde{\varphi}_p = \tilde{\varphi}_f + \alpha k \tilde{T}_e / e$ where $\alpha \sim 3$ **possible large errors!**

$\tilde{T}_e$ measurement desirable

Heat Flux:

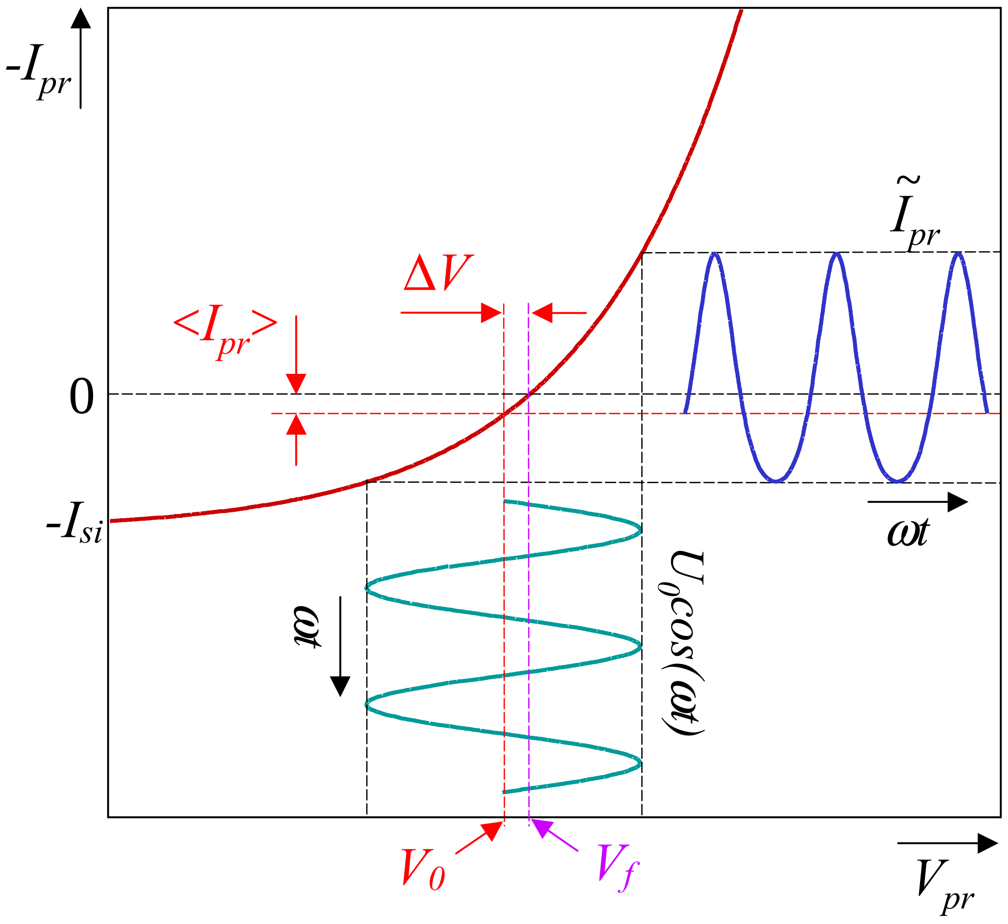
$$Q_r^{ES} = Q_{conv} + Q_{cond} = \frac{5}{2} k T_e \Gamma_r + \frac{5}{2}\frac{n_e}{B_\varphi}\left\langle k\tilde{T}_e \tilde{E}_\theta \right\rangle$$

$\tilde{T}_e$ measurement necessary

Probe Techniques Suitable for $\tilde{T}_e$ Measurements

- Fast-swept single or double probes:
  - Require high sweep voltage (to reach ion saturation) $eU_0 >> kT_e$
    - High power amplifier required; arcing problems likely
  - High sampling speed requirements (to perform fit to I-V characteristic)
- Triple probes:
  - Arguably, do not work well in strongly magnetized plasmas (where the ion Larmor radius is smaller than the pin separation)
  - Spatial resolution is compromised for wavelengths smaller than the pin separation (can be corrected by special pin arrangements)
  - Cable capacitance in the vacuum drive of the DIII-D reciprocating probe is too high to use this method at high frequencies (> 10 kHz)
- Harmonic technique - **chosen for DIII-D**:
  - Relatively low sweep voltage requirements $0.4kT_e \le eU_0 \le kT_e$
  - Only one pin required high spatial resolution
  - Relatively low sampling rate requirements: $f_{sampl} \ge 5 f_{sweep}$

Diagnostic Basics: Current to a DC-Floating Probe Driven by High-Frequency Sinusoidal Voltage



- Non-linearity of the probe’s I-V characteristic causes generation of harmonics in the current spectrum
- To satisfy $<I_{pr}> = 0$ operating DC potential of the probe is shifted from the floating potential:

$$V_0 = V_f - \Delta V$$

where

$$\Delta V = \frac{kT_e}{e}\ln\left(\mathrm{I}_0\left(\frac{eU_0}{kT_e}\right)\right)$$

U_0 - drive voltage amplitude

(Boedo *et al*, Rev. Sci. Instrum. **70** (1999), 2997)

Diagnostic Basics:

Harmonic Expansion of the Probe Current

- Probe current for $V_{pr} < V_p$ (plasma potential) is given by:

$$I_{pr} = I_{si} + I_{se}\exp\left(\frac{e(V_{pr} - V_p)}{kT_e}\right) = I_{si} + I_{se}\exp\left(\frac{e(V_0 + U_0\cos(\omega t) - V_p)}{kT_e}\right) =$$

$$= I_{si} + I_{se}\exp\left(\frac{e(V_0 - V_p)}{kT_e}\right)\exp\left(\frac{eU_0\cos(\omega t)}{kT_e}\right)$$

- Using $\exp(z\cos(\theta)) = \mathrm{I}_0(z) + 2\sum_{k=1}^{\infty}\mathrm{I}_k(z)\cos(k\theta)$ one can get:

$$I_{pr} = \frac{2I_{si}}{\mathrm{I}_0\left(\frac{eU_0}{kT_e}\right)}\sum_{m=1}^{\infty}\mathrm{I}_m\left(\frac{eU_0}{kT_e}\right)\cos(m\omega t) = \sum_{m=1}^{\infty} I_{m\omega}\left(\frac{eU_0}{kT_e}\right)\cos(m\omega t)$$

where $I_{m\omega}\left(\frac{eU_0}{kT_e}\right) = 2I_{si}\,\mathrm{I}_m\left(\frac{eU_0}{kT_e}\right)\Big/\mathrm{I}_0\left(\frac{eU_0}{kT_e}\right)$ - amplitude of m^{th} harmonic

$\mathrm{I}_k(z)$ - Bessel functions of integer order k

Diagnostic Basics:

Series approximation for $eU_0/kT_e < 1$

Bessel functions can be expressed by a series: $\mathrm{I}_k(z) = \sum_{n=0}^{\infty} \frac{z^{2n+k}}{2^{2n+k}(n+k)!\,n!}$

For $z << 1$ only the first term can be used: $\mathrm{I}_k(z) \approx \frac{z^k}{2^k\,k!}$

Hence, for $eU_0/kT_e << 1$:

$$\mathrm{I}_1\left(\frac{eU_0}{kT_e}\right) \approx \frac{eU_0}{2kT_e} \qquad \mathrm{I}_2\left(\frac{eU_0}{kT_e}\right) \approx \frac{1}{8}\left(\frac{eU_0}{kT_e}\right)^2 \qquad \mathrm{I}_3\left(\frac{eU_0}{kT_e}\right) \approx \frac{1}{48}\left(\frac{eU_0}{kT_e}\right)^3$$

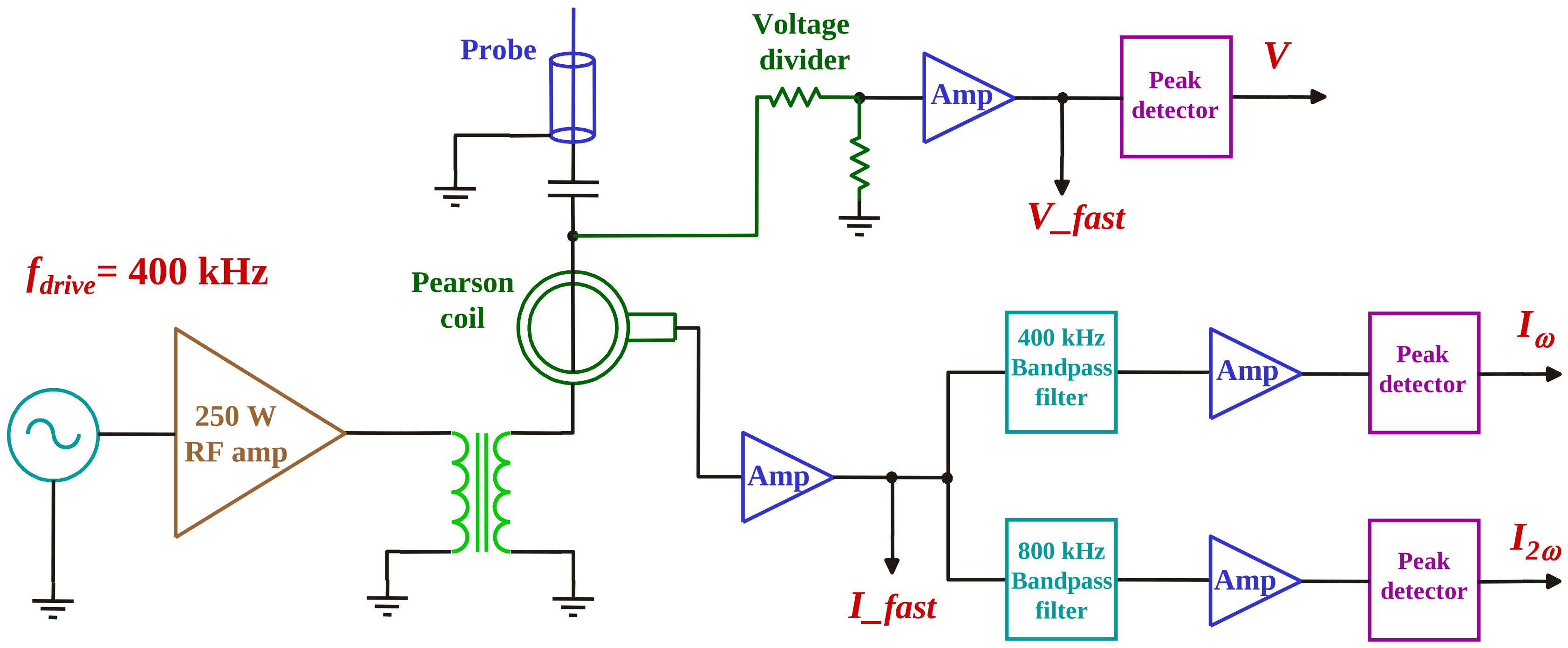
$$\boxed{kT_e \approx \frac{eU_0}{4}\frac{\mathrm{I}_1}{\mathrm{I}_2} = \frac{eU_0}{4}\frac{I_\omega}{I_{2\omega}}}$$

Thus T_e can be determined from the ratio of the amplitudes of 1st and 2nd harmonics

The error of this approximation for $eU_0/kT_e = 1$ is only about 5%

(Boedo *et al*, Rev. Sci. Instrum. **70** (1999), 2997)

Diagnostic Layout - Present

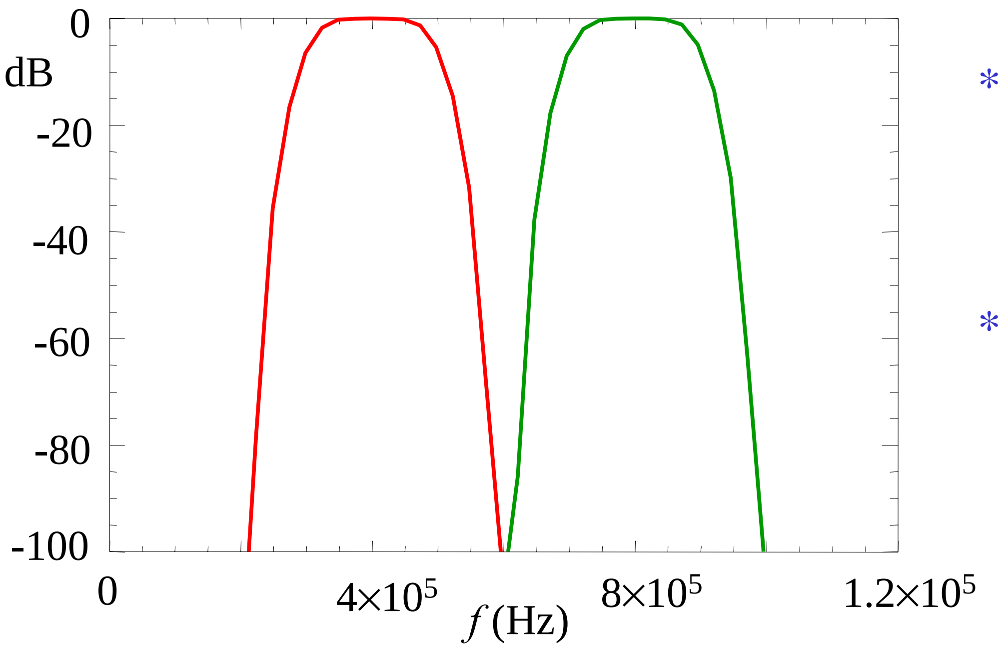


Dual harmonic detection system:

- Both detected (I_ω, $I_{2\omega}$) and raw (“fast”) signals are recorded
- “Fast” signals are digitized at 5 MHz and processed digitally to extract the amplitudes of the current harmonics and drive voltage

Digital Filtering

- Digital filtering is performed in IDL using standard IDL functions DIGITAL_FILTER and CONVOL
- Filers typically used are Finite Impulse Response (FIR) Kaiser filters of the order $N = 40 \div 100$ with ripple amplitude $A < -50 \div -100$ dB and pass band half-width $df = 100 \div 200$ kHz

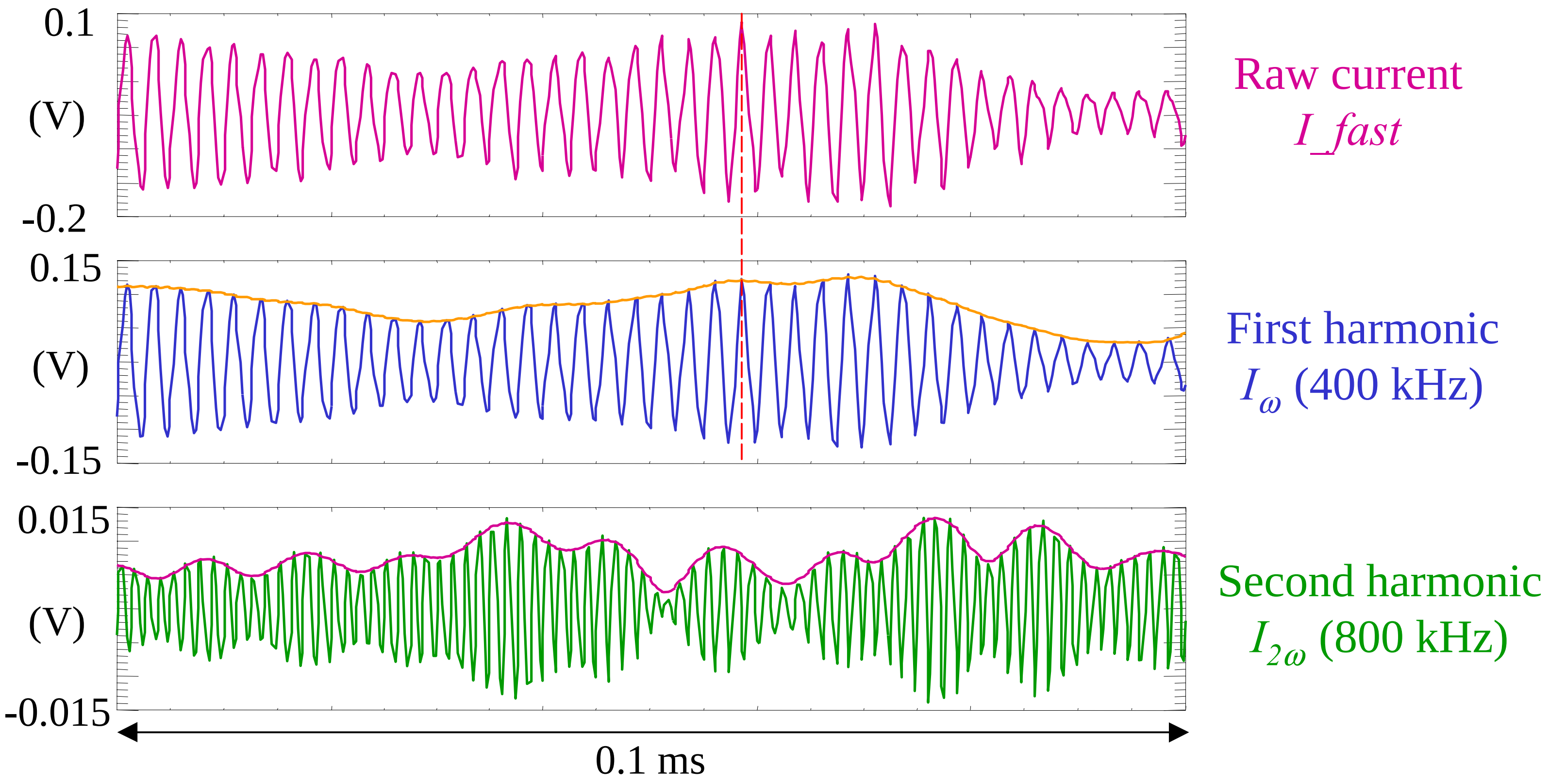


* Frequency response of FIR Kaiser filters used for first and second current harmonics

* Filter parameters:
$N = 100$
$A < -100$ dB
$df = 100$ kHz

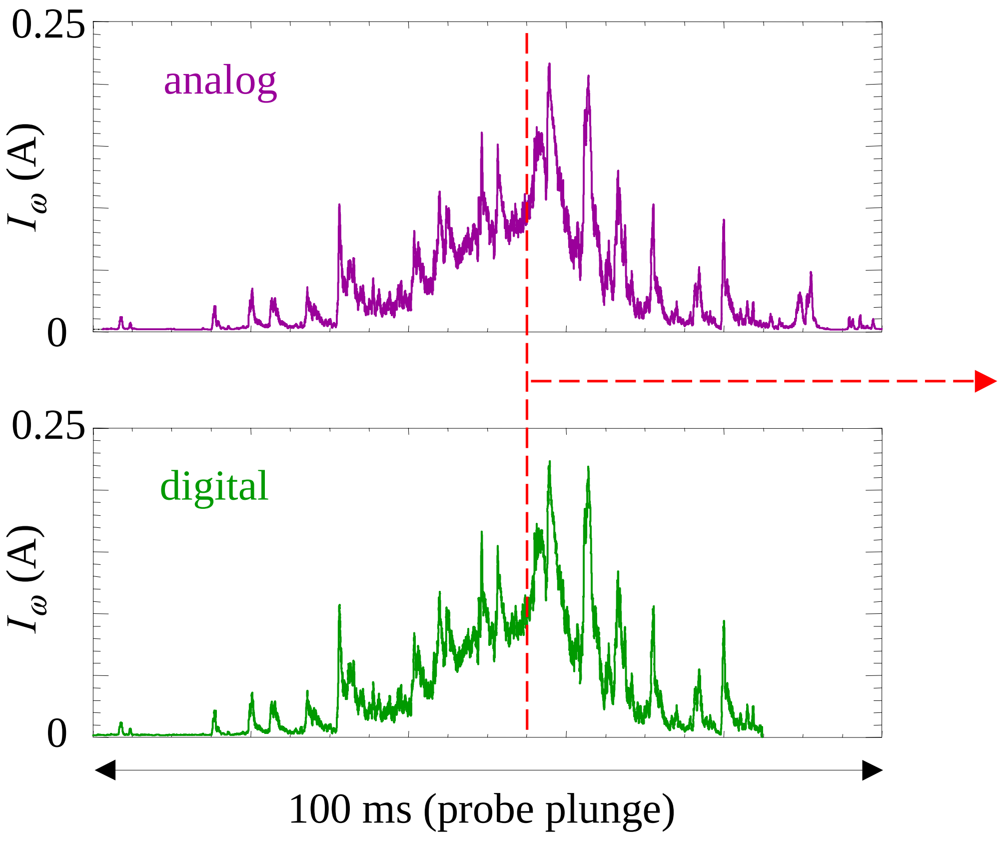
Digital Filtering Does Not Introduce Phase Delay

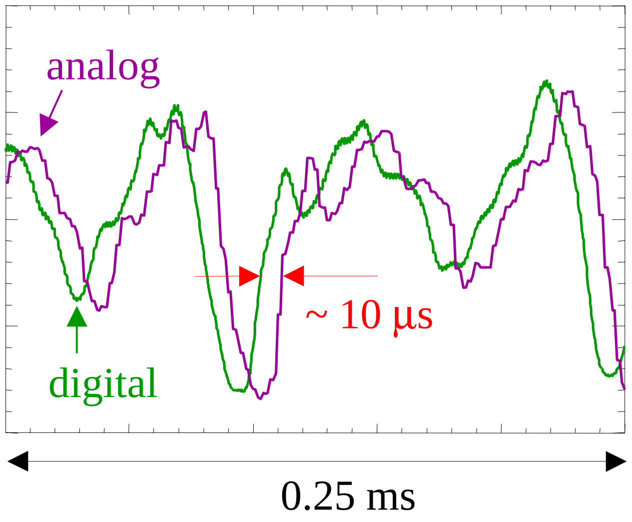
Raw current signal and harmonic signals obtained by digital filtering



Digital Harmonic Detection Is Superior to Analog

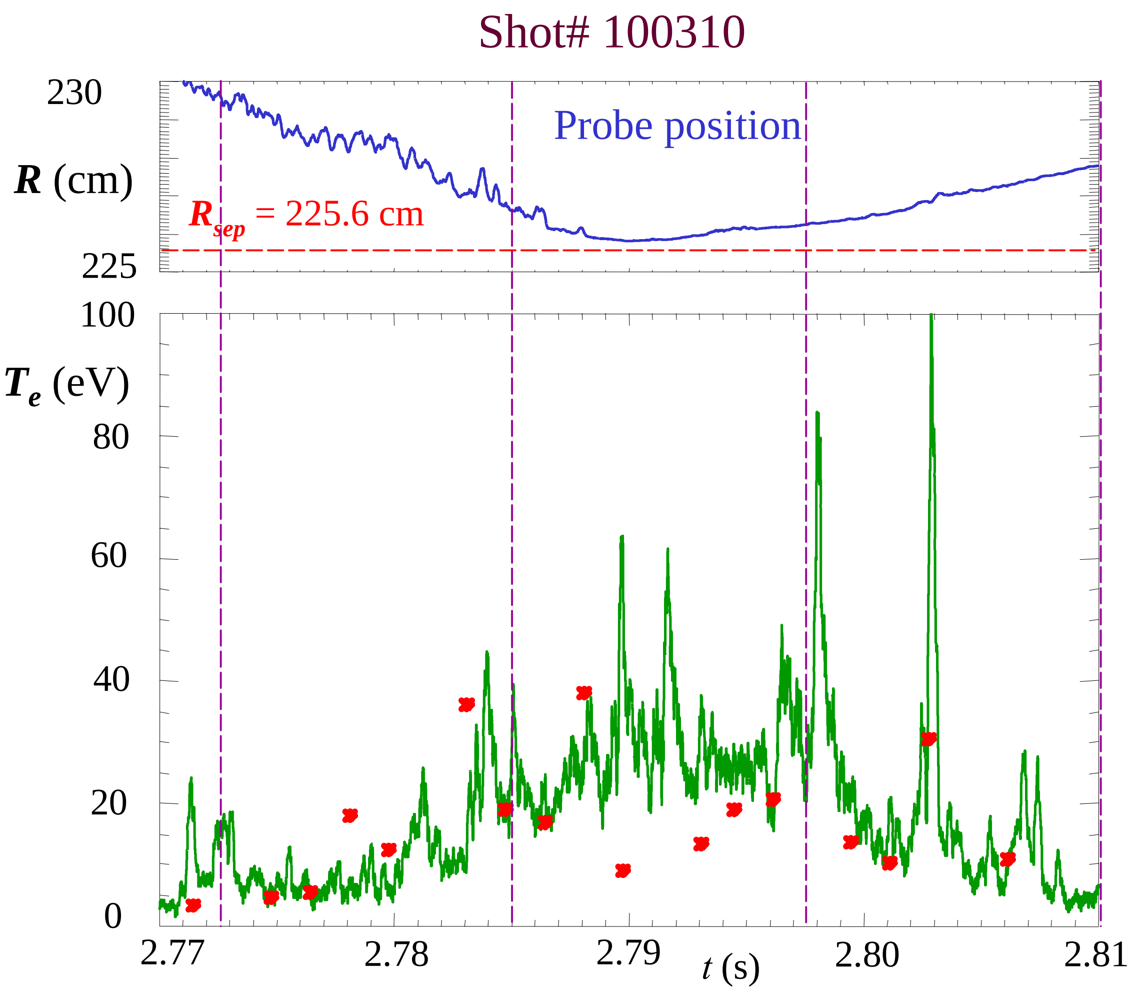
Amplitude of the 1st current harmonic obtained by analog and digital methods





Analog circuitry introduces time delay of about 10 μs making it not suitable for correlation measurements at high frequencies

Results: Comparison with Swept Double Probe



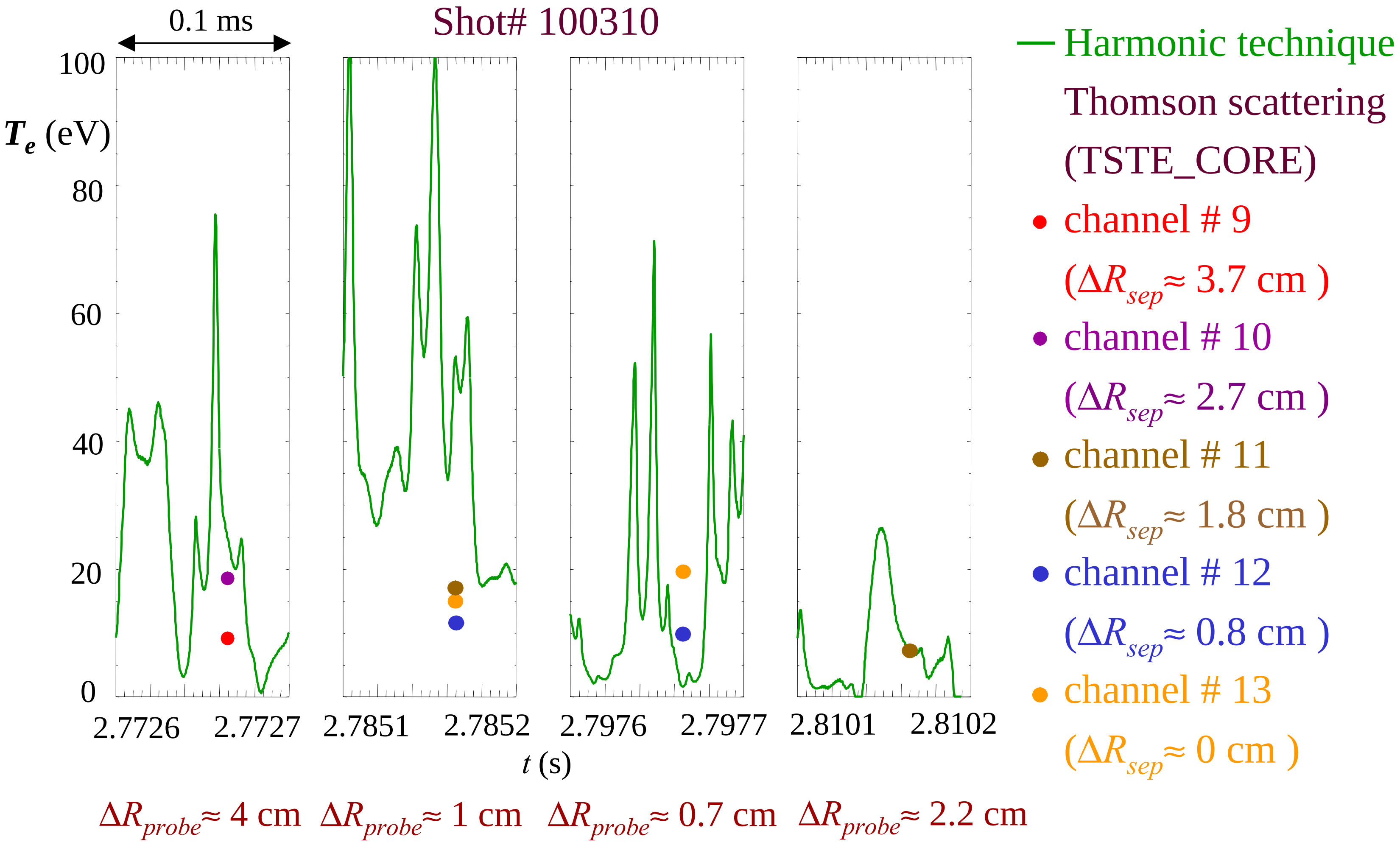
— Harmonic technique (averaged over 0.2 ms)

● Swept double probe (on the same drive)

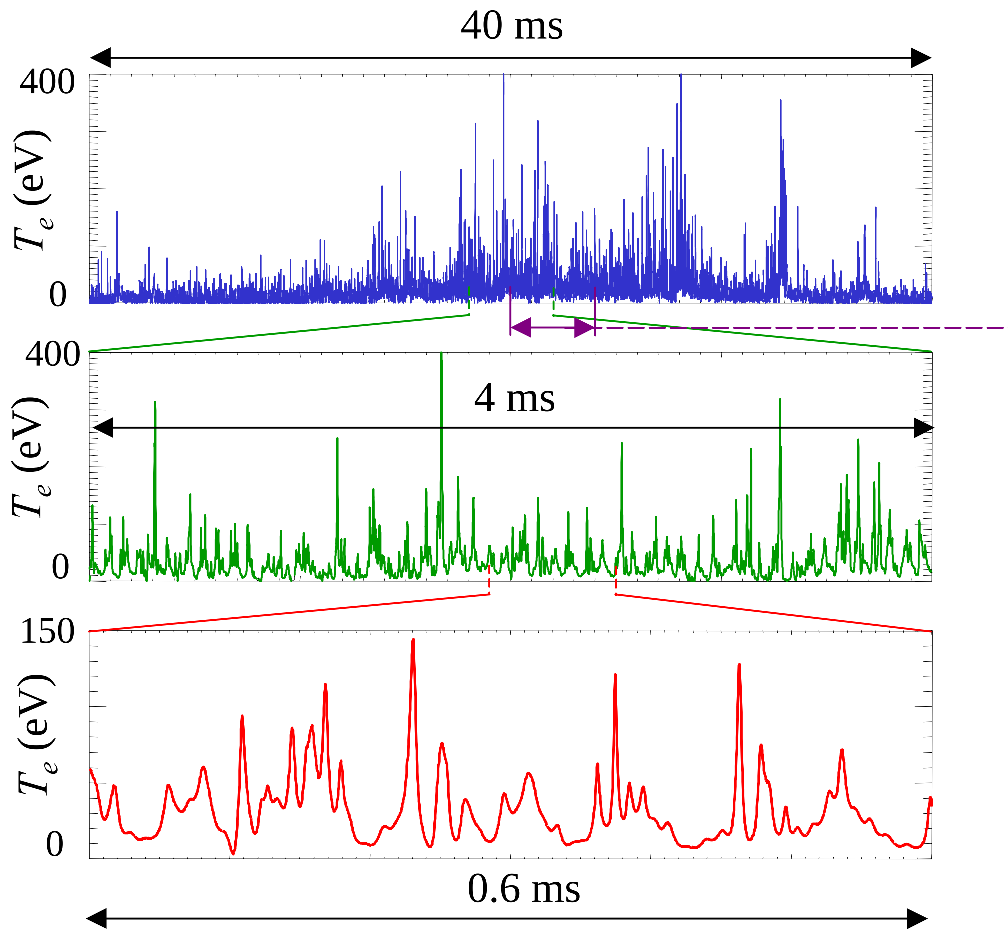
Both techniques are in reasonably good agreement

- - Thomson Scattering pulses (see next slide)

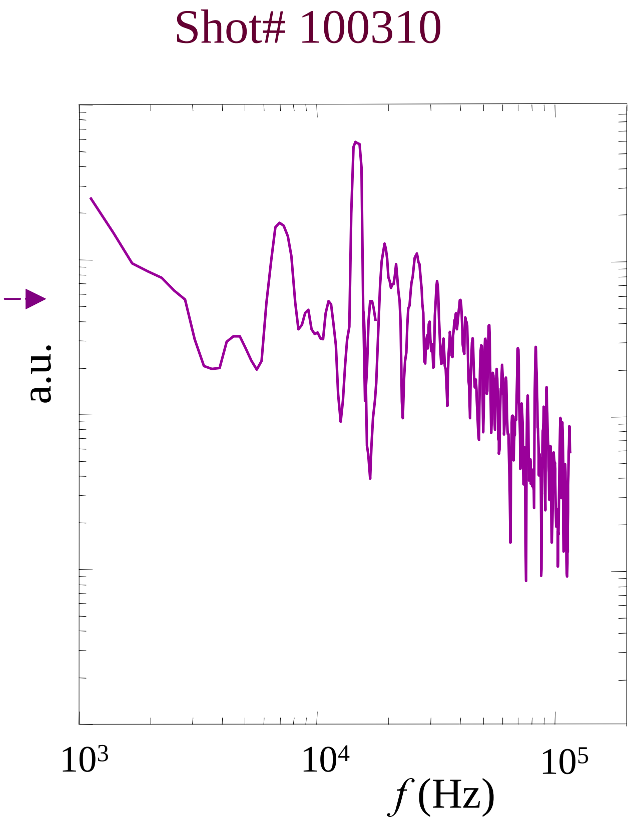
Results: Comparison with Thomson Scattering



Results: Edge Electron Temperature Fluctuations



Fluctuating Temperature on Different Time Scales



Power Spectrum of the Temperature Fluctuations

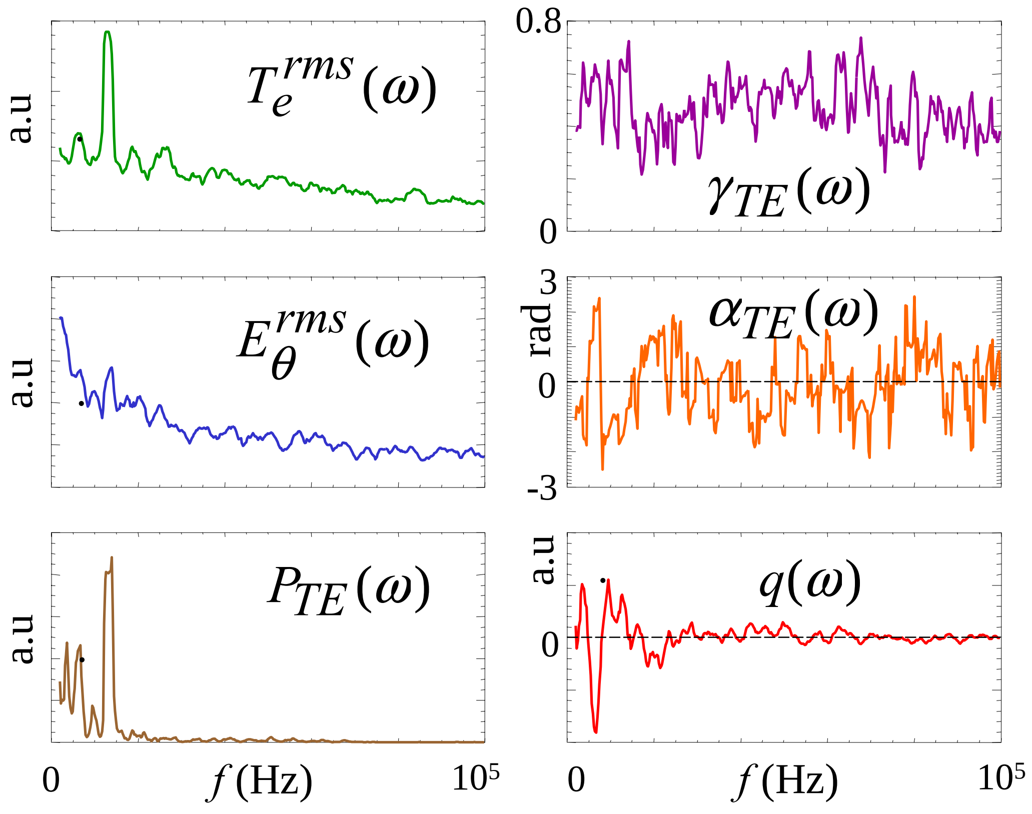
Results: Factors Contributing to Turbulent Heat Flux

$$Q_{cond} = \int_0^\infty q(\omega)\,\mathrm{d}\omega, \qquad q(\omega) = \frac{5}{2}\frac{n_e}{B_\varphi} T_e^{rms}(\omega) E_\theta^{rms}(\omega) \gamma_{TE}(\omega) \sin(\alpha_{TE}(\omega))$$

$\tilde{T}_e$ amplitude

$\tilde{E}_\theta$ amplitude

cross-power



coherence

cross-phase

heat flux spectral density

Diagnostic Upgrade: Drive Voltage Feedback

- For the linear approximation to work and to avoid approaching electron saturation, the drive voltage amplitude U_0 should be kept below T_e
- For the signal to noise ratio to be high enough the amplitude of the second harmonic should be large enough $I_{2\omega} \geq 0.1\ I_\omega$
- Therefore U_0 should be kept in the following range:

$$\boxed{0.4\frac{kT_e}{e} \leq U_0 \leq \frac{kT_e}{e}}$$

- As the probe plunges towards the separatrix, T_e changes from below 10 eV to above 100 eV, therefore, **drive voltage feedback is necessary**
- Practically voltage feedback can be implemented by using an analog divider to determine the ratio of current harmonics (or U_0 / T_e) and providing feedback to the function generator to keep this ratio within required limits

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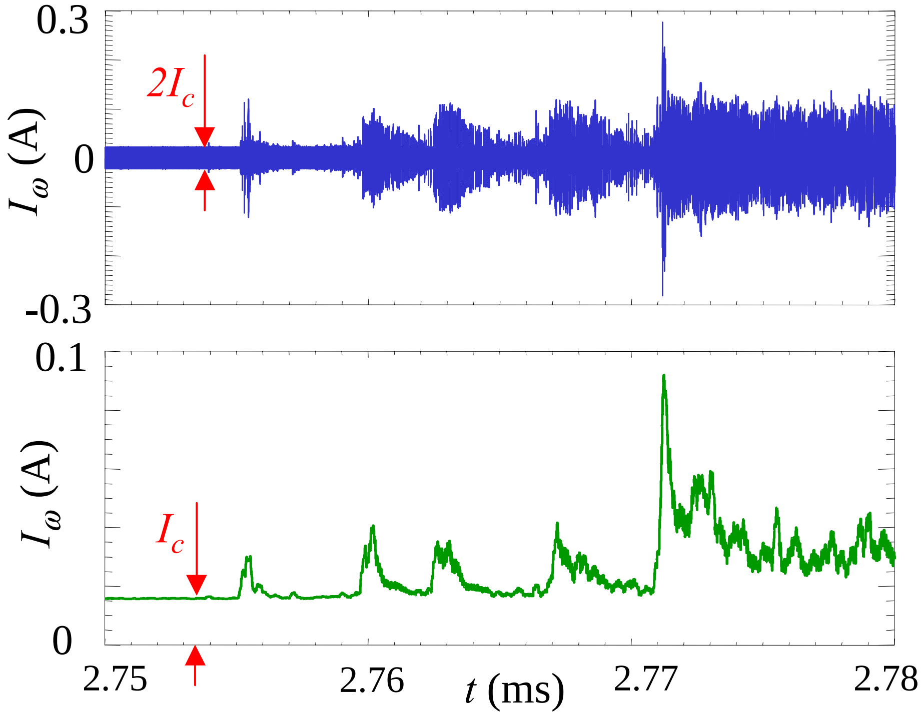
Diagnostic Upgrade: Leakage Current Compensation

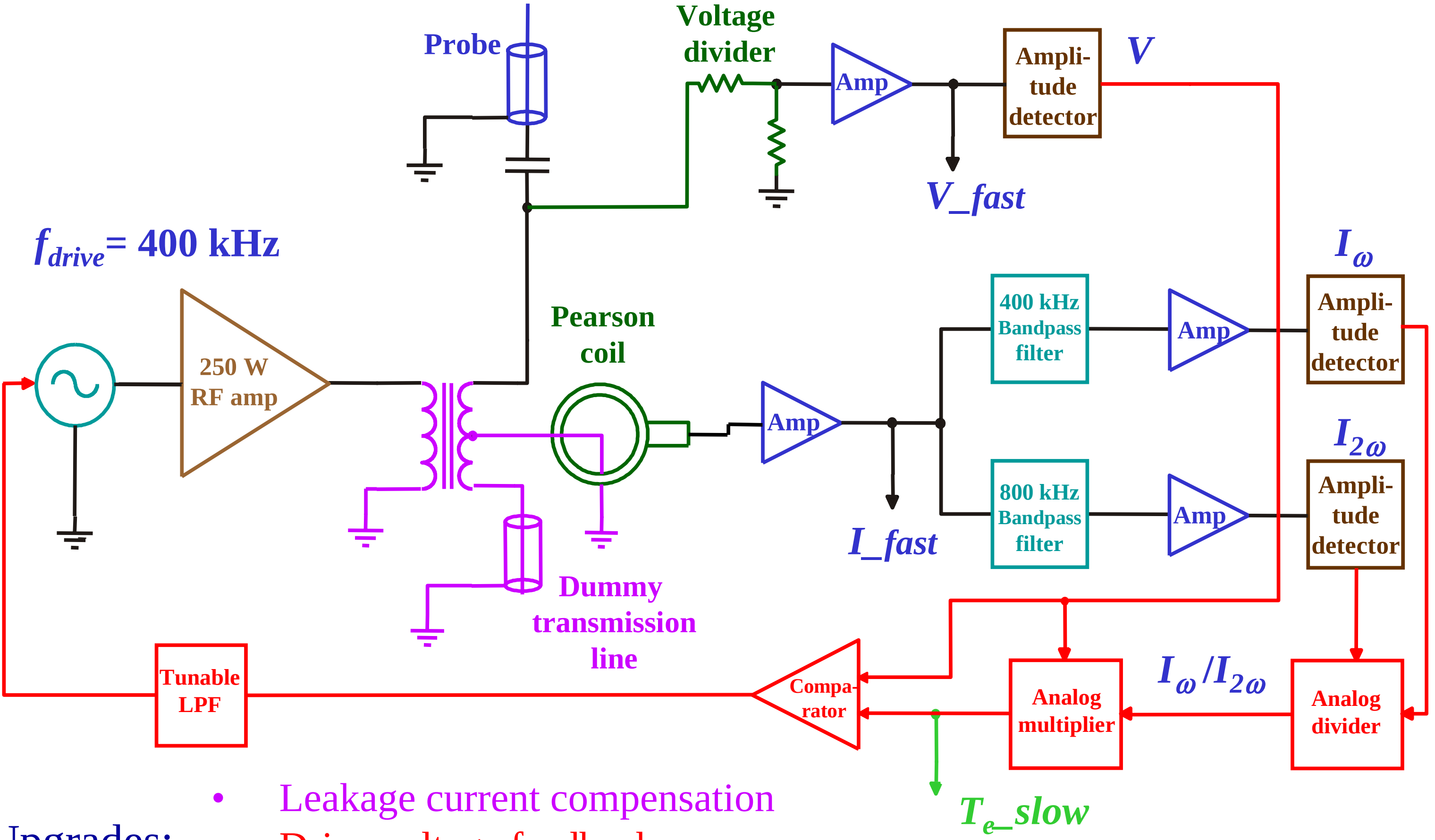


— 1^{st} current harmonic I_ω after filtering

— detected amplitude of I_ω (averaged over 0.2 ms)

- The offset I_c in the amplitude of the 1^{st} current harmonic I_ω is caused by capacitive leakage to the ground in the transmission line to the probe
- For constant drive voltage amplitude I_c can be substracted from the detected amplitude of I_ω
- Simple substraction will not work with voltage feedback in place
- Leakage current can be partly compensated using a center tap transformer and a matched dummy transmission line

Diagnostic Layout - Upgraded



Upgrades:

- Leakage current compensation
- Drive voltage feedback
- Slow (10 kHz) T_e output for long pulse capability

Summary

- Suitability of the harmonic technique for fast edge electron temperature measurements in DIII-D has been demonstrated
- First T_e results from DIII-D are in agreement with swept double probe and Thomson scattering data
- First measurements of the turbulent heat flux in DIII-D have been performed
- Digital harmonic detection procedure has been developed
- Diagnostic upgrades before the next experimental campaign will include drive voltage feedback and leakage current compensation
- Bandwidth increase to 500 kHz is under consideration