Details and Results from the FIReTIP Electronics Upgrade on NSTX

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Abstract

The IF electronics system of the Multichannel Far Infrared Tangential Interferometer/Polarimeter (FIReTIP) system on the National Spherical Torus Experiment (NSTX) was upgraded in July 2009 to greatly extend its ability to monitor high frequency density fluctuations. The measurements are essential in understanding transport physics issues in NSTX as well as for future devices such as ITER in which fundamental understanding of microturbulence MHD issues is essential. The electronics, which were previously limited to ~250 kHz, have now been upgraded to > 3 MHz when operating as an interferometry-only configuration, and to ~800 kHz when operated as a simultaneous interferometer/polarimeter system. New electronics are also being tested to monitor 30 MHz density fluctuations induced by high harmonic fast wave heating. Experimental details and test results of the new electronics will be presented.

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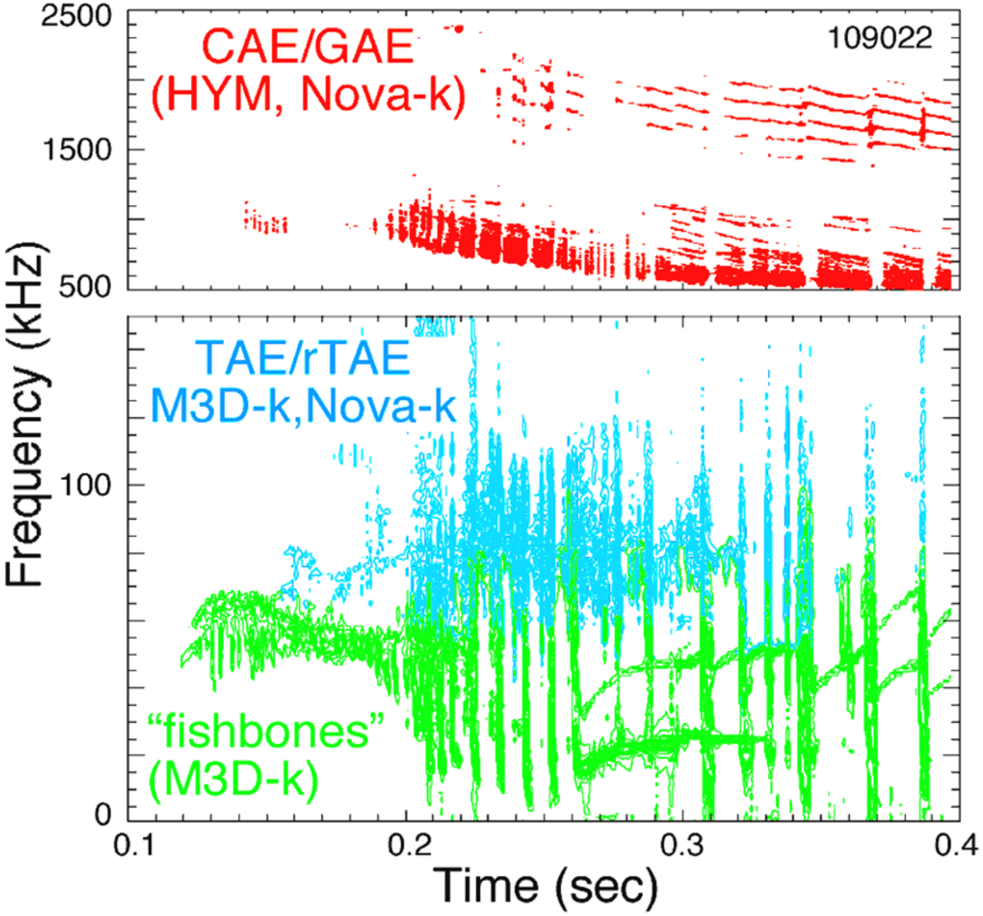
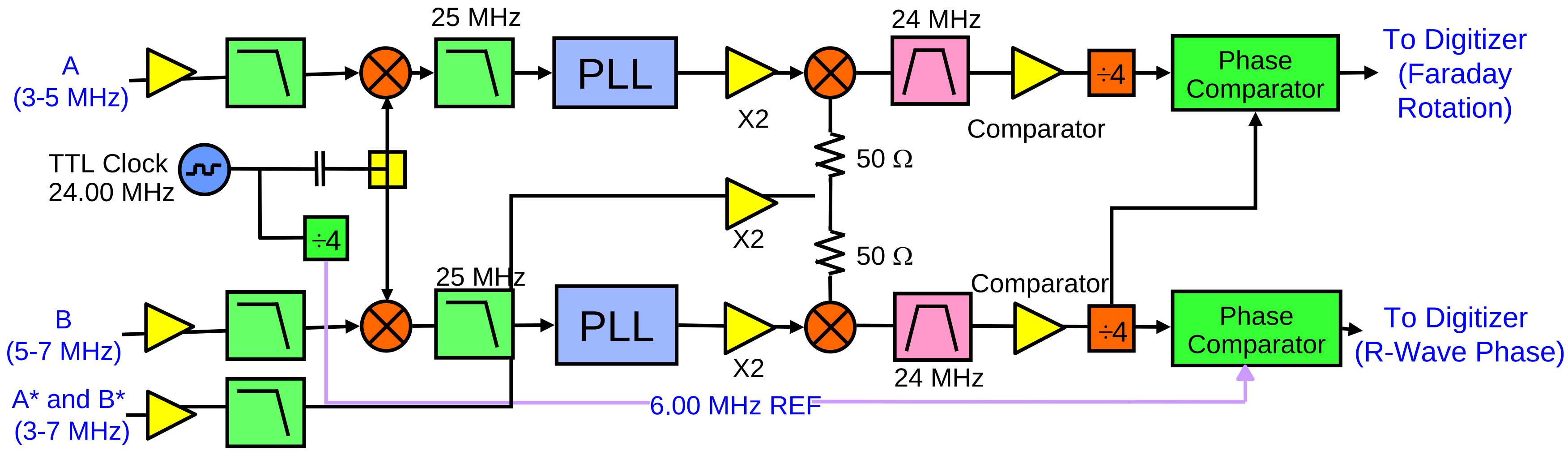
Motivation for Increased Bandwidth

- The video bandwidth of the FIReTIP system was previously limited to ~250 kHz
- A wide range of kinetic instabilities exist on NSTX with frequencies far in excess of 250 kHz, such as
  - Toroidal Alfvén eigenmodes (TAEs)
  - Resonant TAEs (rTAEs)
  - Compressional Alfvén eigenmodes (CAEs)
  - Global Alfvén eigenmodes (GAEs)
- A significant increase in video bandwidth will allow these instabilities to be studied using FIReTIP



From M. Peng, "NSTX Research Plan – FY05-07," OFES Budget Planning Meeting FY-07, available online at http://www.nstx.pppl.gov/bpm/03-2005/Mpeng_Science_FY05-07.pdf (2005).

Old FIReTIP Electronics System



- To increase signal amplitude for possible signal processing
- Plasma signals consist of R- and L-waves, mixed with reference signals, up-converted to 24 MHz and bandpass (BP) filtered, and then sent to phase comparators and digitizers for phase calculation

Phase locked loops PLL	□ Reduce noise of reference signals; □ Track FIR laser drifts up to 100 kHz □ Not applied to plasma signals as the low modulation bandwidth (~60 kHz) VCOs used in the PLLs are not sufficiently fast for the plasma signals
	□ Bandpass filters employed to separate the R- and L-wave signal components □ Effective bandwidth is ~250 kHz due to filter bandwidth
Phase Comparator & digitizer	□ Fringe counter circuits employed with ~300 kHz lowpass filters □ 14 bit, 1.25 MHz digitizers employed

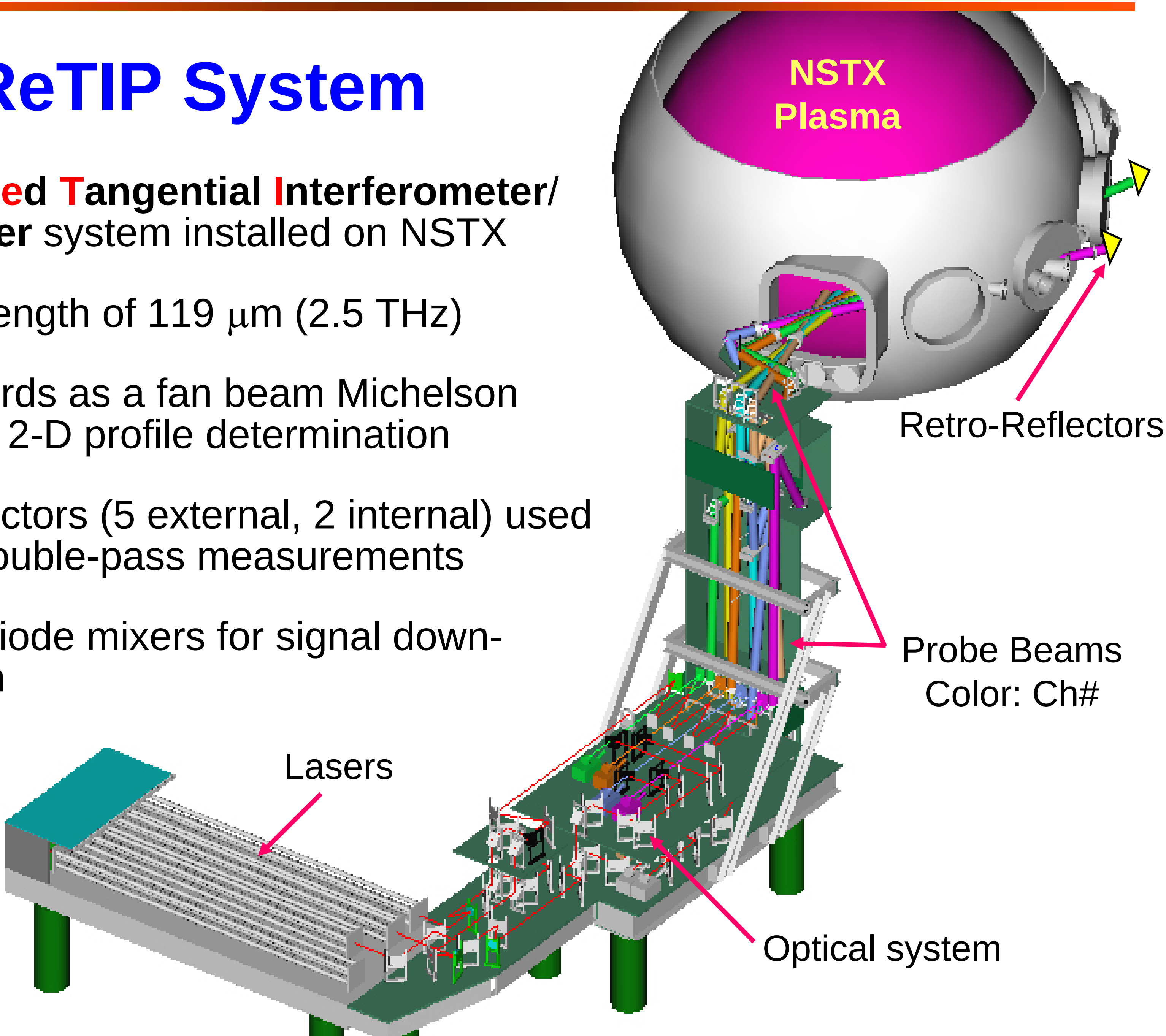
Video bandwidth is limited to ~250 kHz (due primarily to BP filters)

FIReTIP Bandwidth Upgrade Approach

- Employ high modulation bandwidth voltage-controlled oscillators (VCOs) for phase-locked loop (PLL) circuits which can be applied to plasma signals as well as reference signals
  - VCOs now available with 3 dB modulation bandwidth > 6 MHz
- Turn off one FIR laser for maximum bandwidth in interferometry-only measurements (eliminates need for bandpass filters)
  - Maintaining a ~6 MHz IF frequency enables a ~4 MHz video bandwidth to be achieved
- Employ wider bandwidth, sharper edge bandpass filters to separate out R- and L-wave signal components as needed
  - Simultaneous interferometry/polarimetry measurements with ~1 MHz bandwidth
- Perform phase comparison measurements at high frequencies (previous version employs 24.0 MHz) to permit higher cutoff frequency lowpass filters to be employed
  - Lowpass filters with auto-selected 1 MHz/4 MHz bandwidths (choice of filter depending on mode of operation employed)

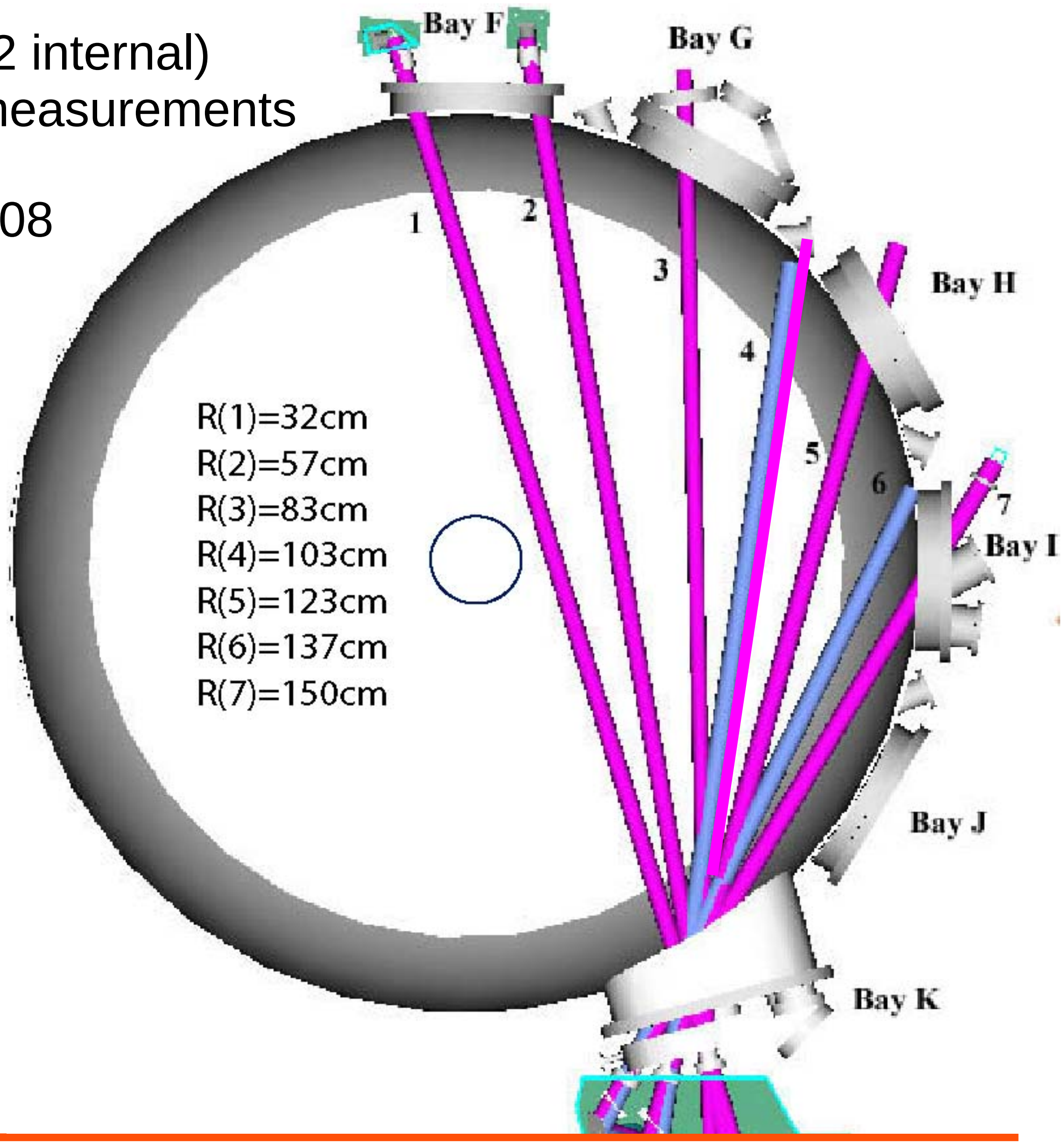
The FIReTIP System

- **Far InfraRed Tangential Interferometer/ Polarimeter** system installed on NSTX
- FIR wavelength of 119 μm (2.5 THz)
- Seven chords as a fan beam Michelson system for 2-D profile determination
- Retro-reflectors (5 external, 2 internal) used to make double-pass measurements
- Schottky diode mixers for signal down-conversion

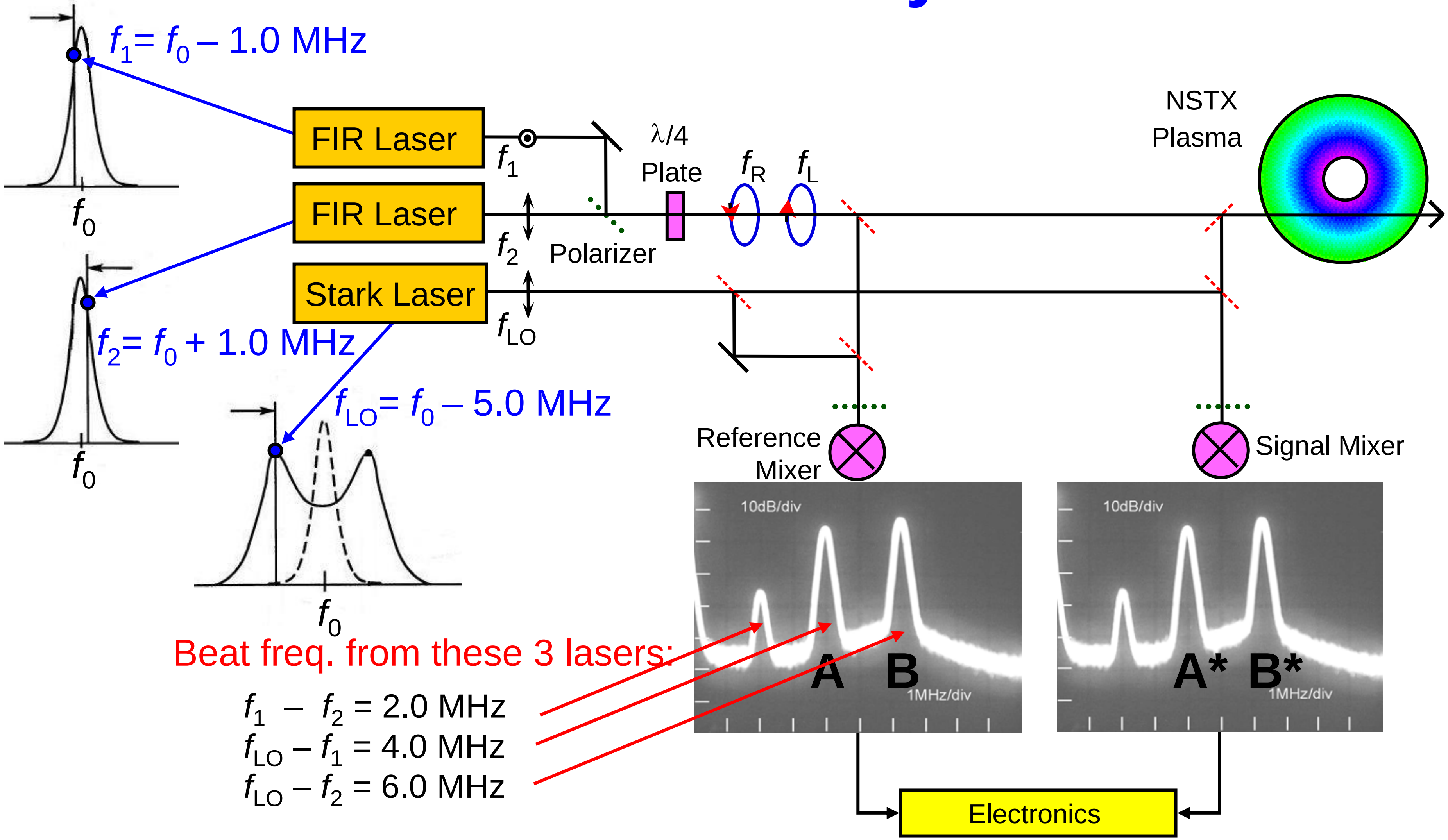


FIReTIP Plasma Coverage

- Retro-reflectors (5 external, 2 internal) used to make double-pass measurements
- 6 channel operation as of 2008
- Channels #1 and #2 used as overall density monitors
- Channels #3, #4 and #5 monitor core fluctuations
- Channels #5 and #7 monitor edge fluctuations

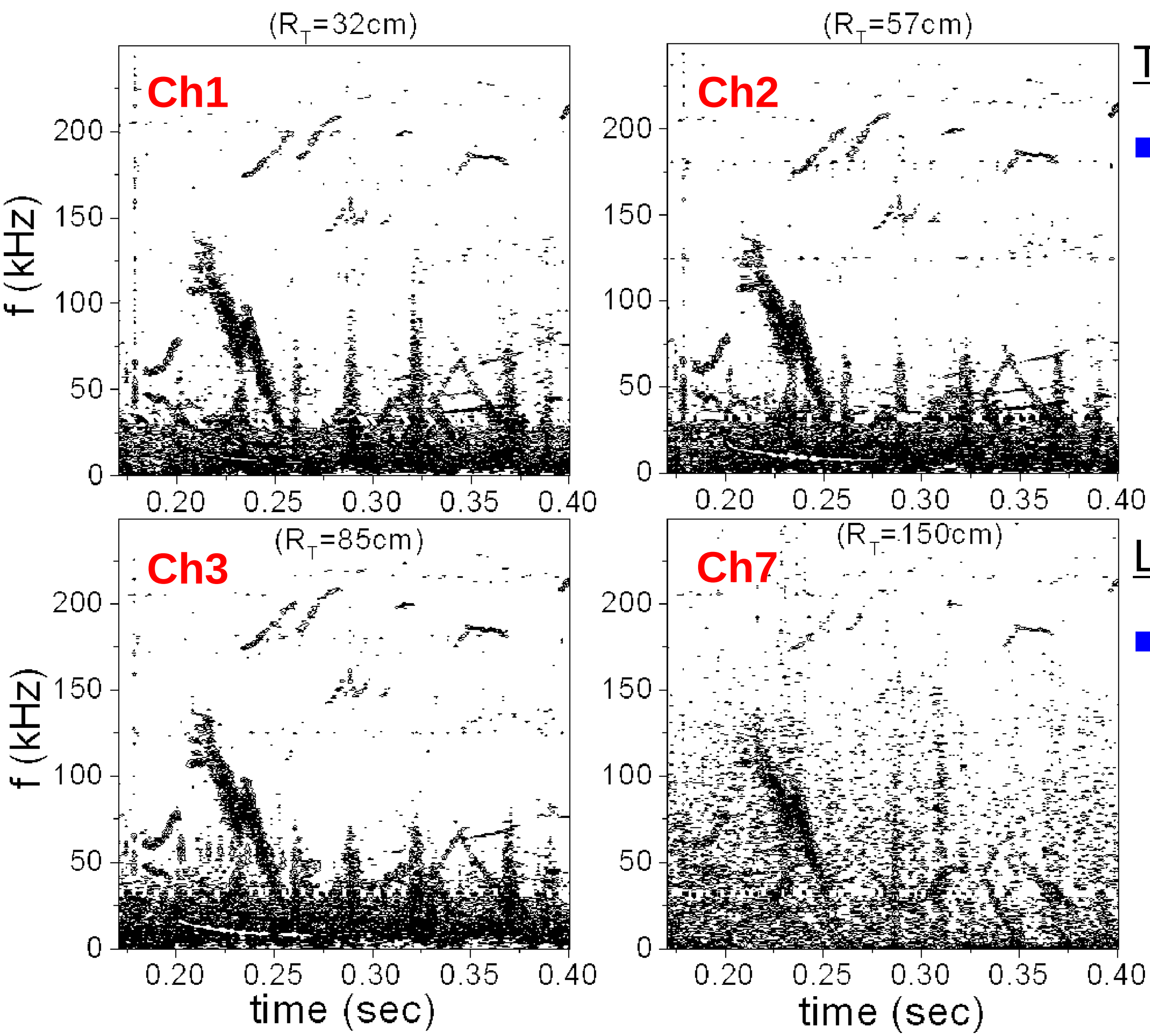


NSTX FIReTIP System



Polarimetry: phase difference of **(A*–B*)**
Interferometry: phase difference of **(B–B*)**

Fluctuations Observed with Previous System



Electron density fluctuation spectrum of discharge #113655

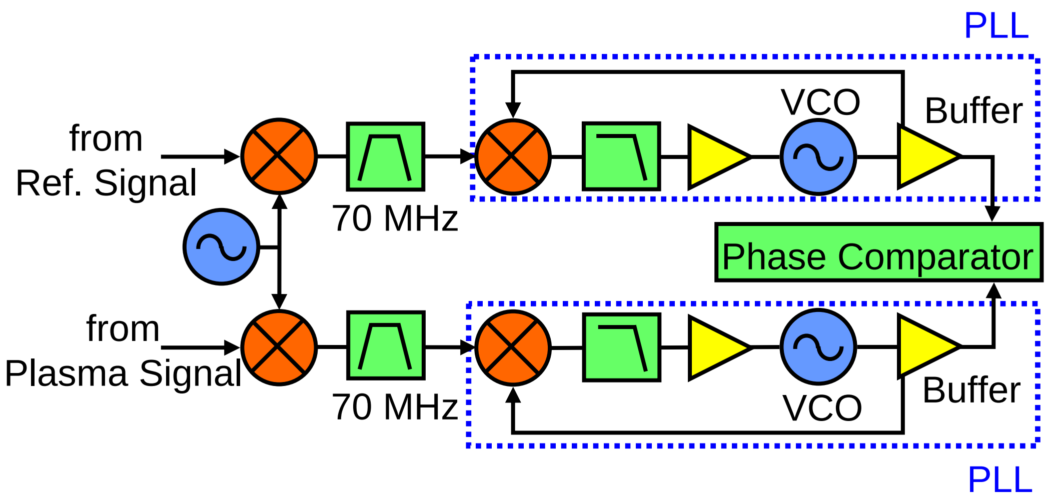
<u>TAE modes (150~200 kHz)</u>

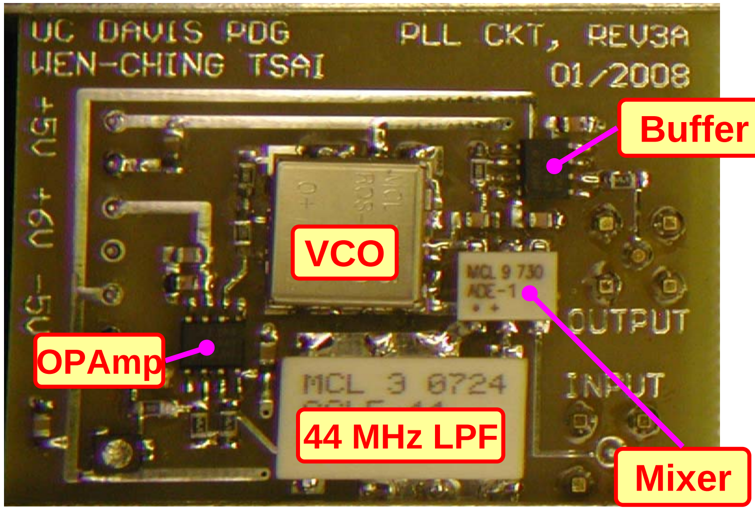
- Magnetic coil data showed similarity and difference in different channels

<u>Localized fishbones</u>

- Similarity observed in Channels 1, 2 and 3 is due to plasma chords spanning the entire core region

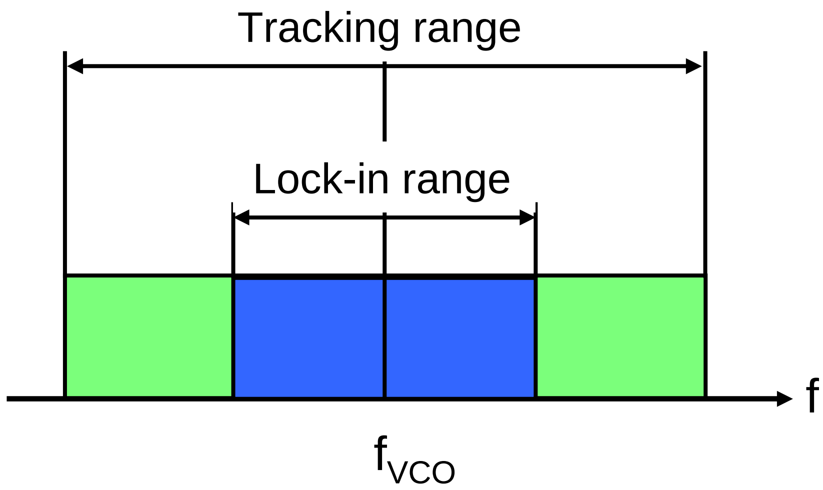
Step 1: New Phase Locked Loop Circuits





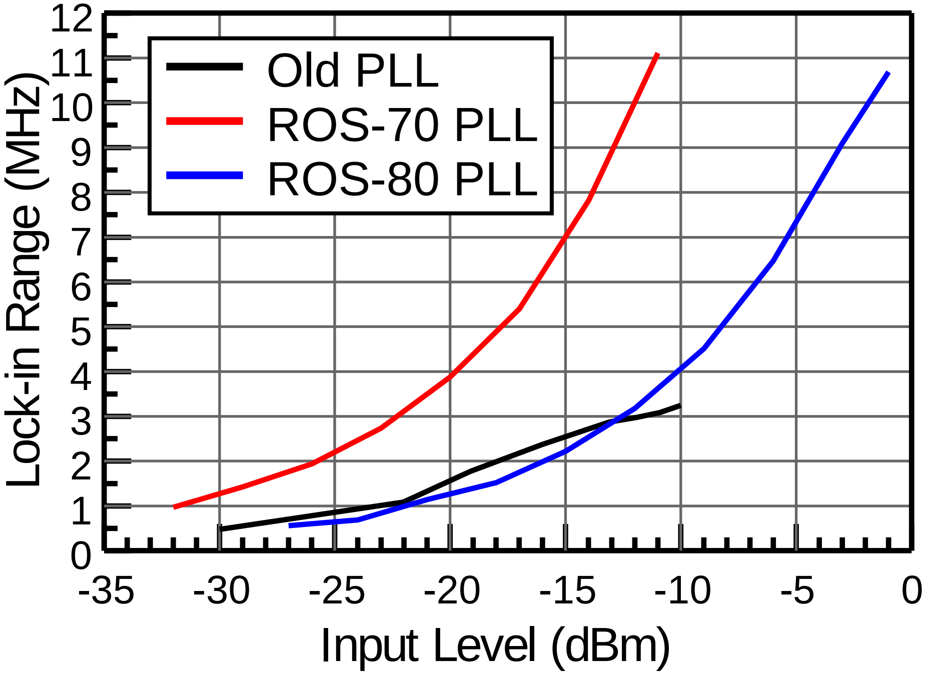
- A phase-locked loop (PLL) consists of a phase detector, low pass filter, and VCO.
- Feedback forces the VCO frequency to settle at the input frequency with a constant phase angle between the VCO and the input signal.
- A VCO with modulation bandwidth greater than 6 MHz can take be employed to clean up FIReTIP signals while retaining all phase flucutations up to a modulation bandwidth of ~4 MHz.

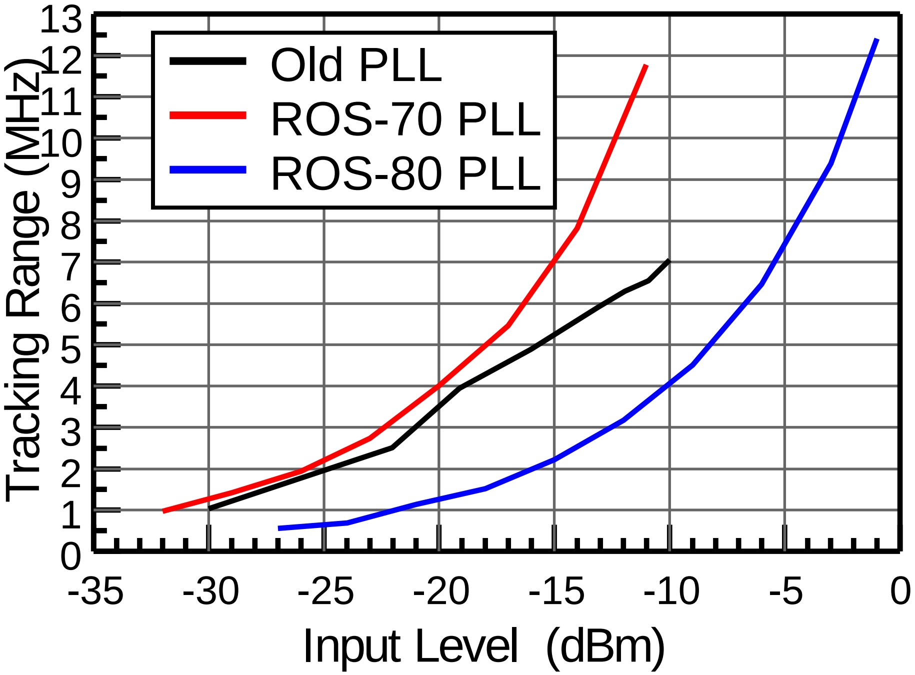
PLL Phase-Tracking Terminology



- FIReTIP previously employed PLLs only to track FIR laser frequency drifts. Here, VCO modulation bandwidths of ~100 kHz and PLL tracking ranges of ~2 MHz are sufficient.
- New PLLs need to be developed with significantly increased lock-in and tracking ranges.
  - Lock-in range measures the frequency range over which the input signal can be pulled-in to lock.
  - Tracking range measures the frequency range over which the input signal remains locked.

PLL Phase-Tracking Performance



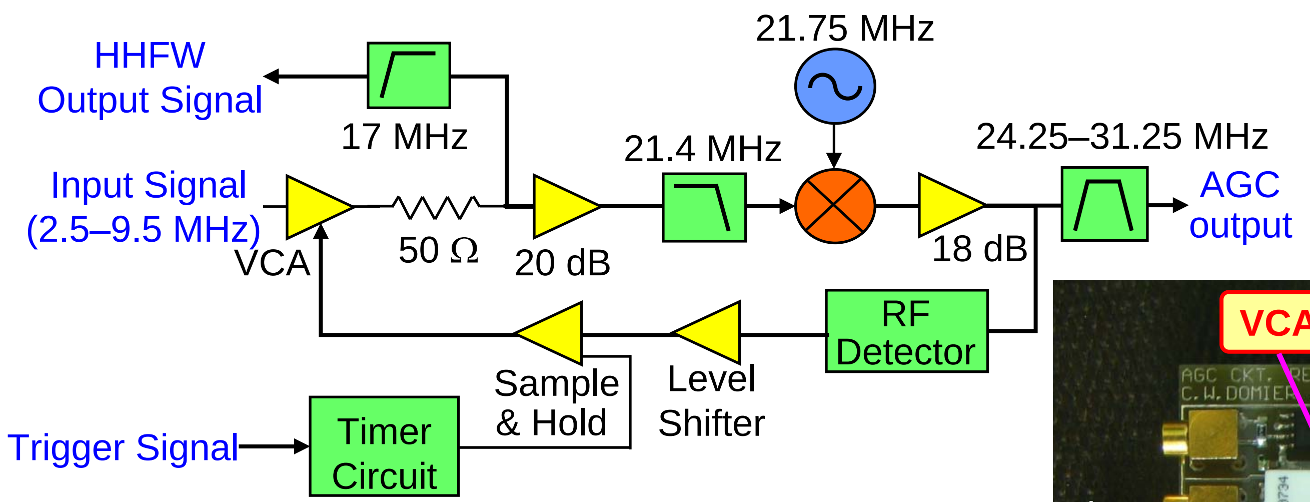


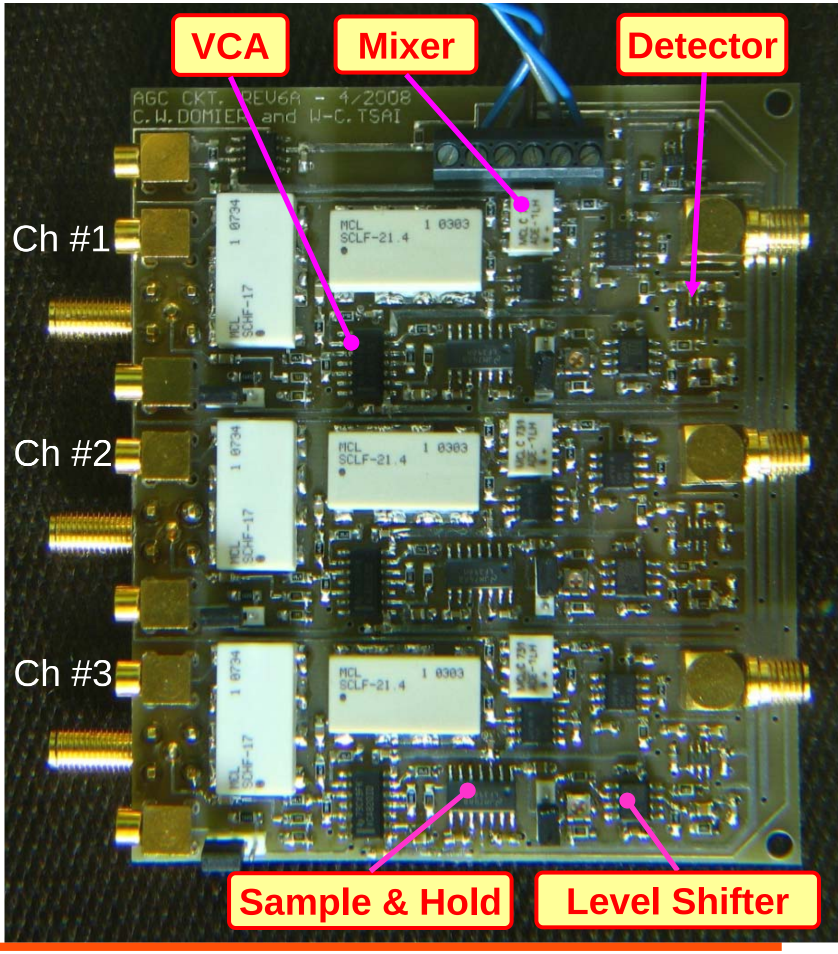
VCO Model	Frequency (MHz)	Phase Noise (dBc/Hz) SSB @Offset Freq.				3 dB Mod. BW
		1 kHz	10 kHz	100 kHz	1 MHz	
POS-50 (Old)	25 – 50	-88	-110	-130	-150	100 kHz
ROS-70-119	55 – 80	-93	-122	-143	-162	17 MHz
ROS-80-7119	76 – 89	-100	-124	-145	-165	6 MHz

Implications of Step 1 Tests

- Frequency upconversion is required
  - High modulation bandwidth VCOs operate at frequencies well above that of the input FIReTIP signals (which fall in the range of 2-10 MHz), requiring input signals to be upconverted to VCO frequencies
  - Single sideband upconversion is highly preferred, as the unwanted sideband signals result in spurious PLL output products
- Lock-in and tracking ranges strongly dependent on input signal level
  - Higher signal levels result in higher lock-in and tracking ranges
  - Automatic gain control (AGC) circuitry, applied to the input signal prior to phase-locking, is essential to obtaining the highest levels of phase-locking
- Overview of new approach
  - Input signal first amplified using AGC circuitry
  - Resultant signal is upconverted to frequencies well above the desired modulation frequency of ~4 MHz
  - Upconverted signal is bandpass filtered to remove unwanted sideband and other spurious mixer products
  - Need for a wide bandwidth filter (min. 7 MHz wide) with high stopband rejection results in the need to implement a two-step upconversion process

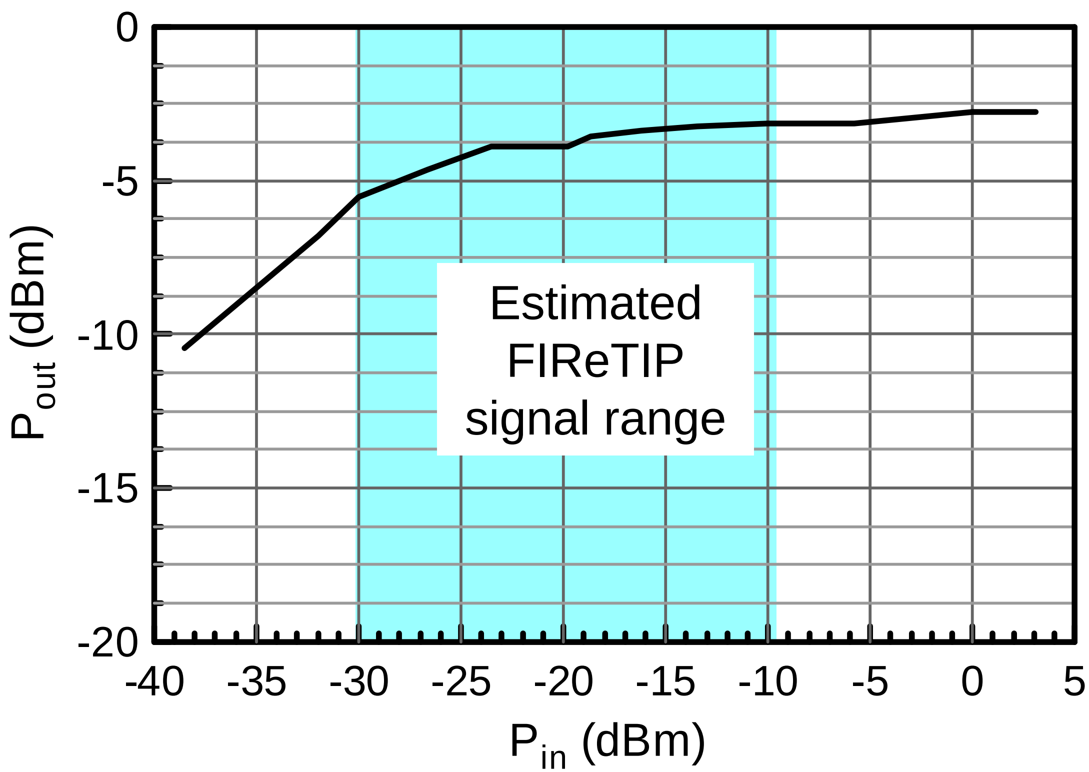
Step 2: AGC and Upconversion Circuits



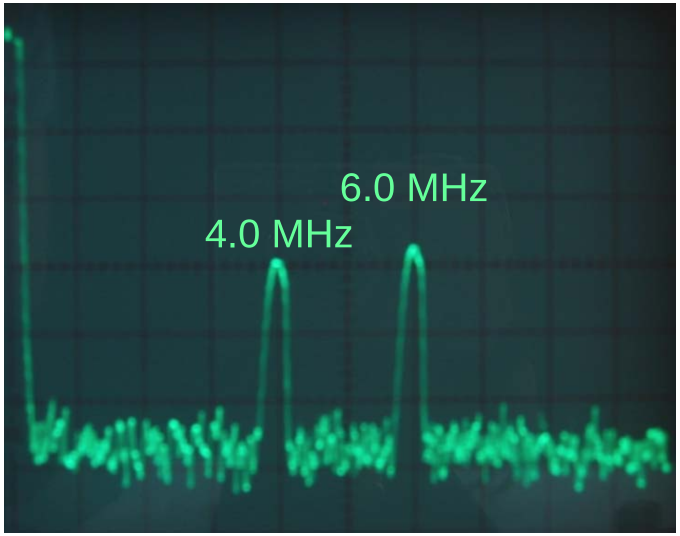


- Input signal levels range from -30 to -10 dBm
- Voltage controlled amplifier (VCA)
  - Variable gain (>20 dB dynamic gain range) set by the AGC feedback path
  - Good linearity (harmonic distortion < 42 dBc)
  - Gain can be “locked” during plasma discharge to avoid gain-induced phase shifts
- Low frequency (2.5–9.5 MHz) signals up-converted by 21.75 MHz
  - Applied to both plasma and reference signals
- A parallel circuit supplies 30.0 MHz HHFW output signal for detection

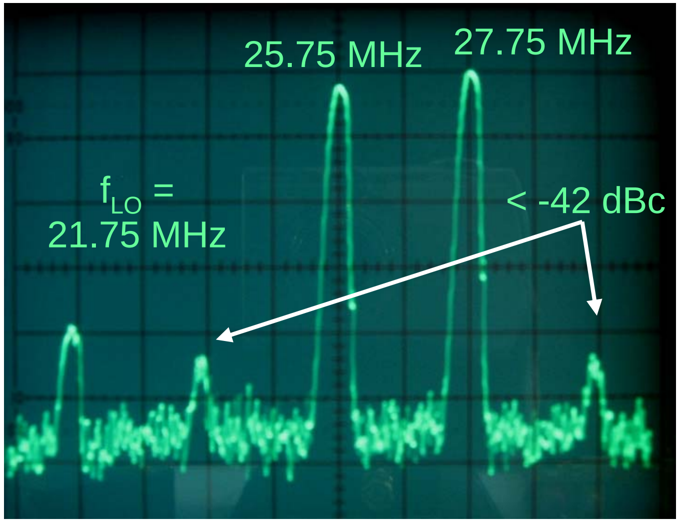
AGC Test Circuit Performance



Input signals



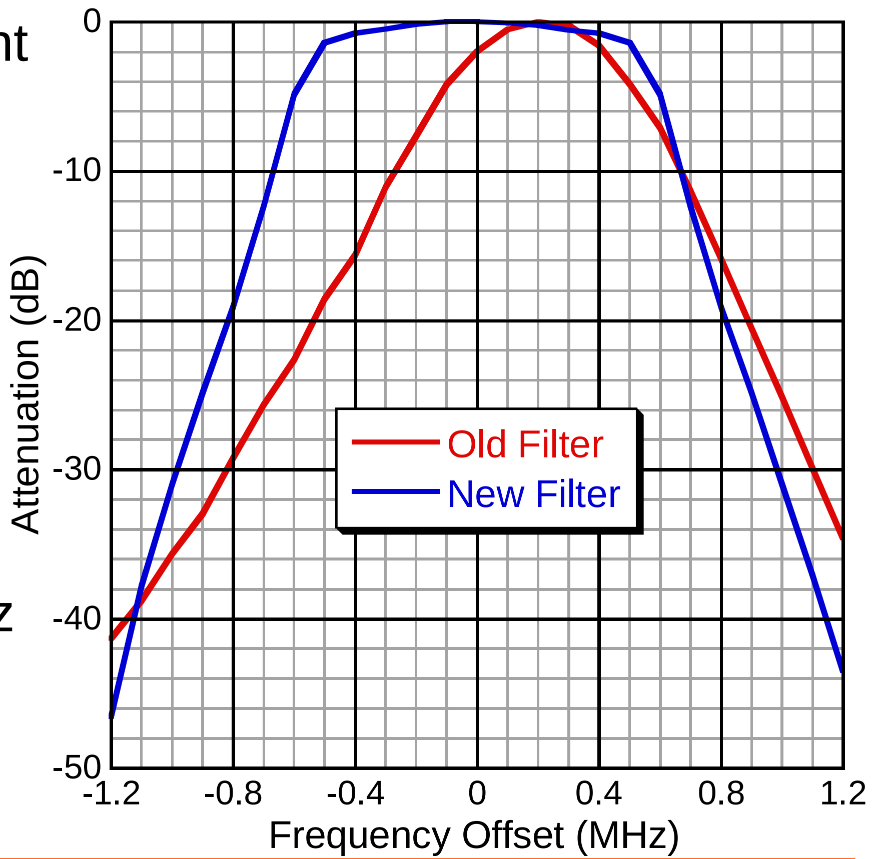
Output signals



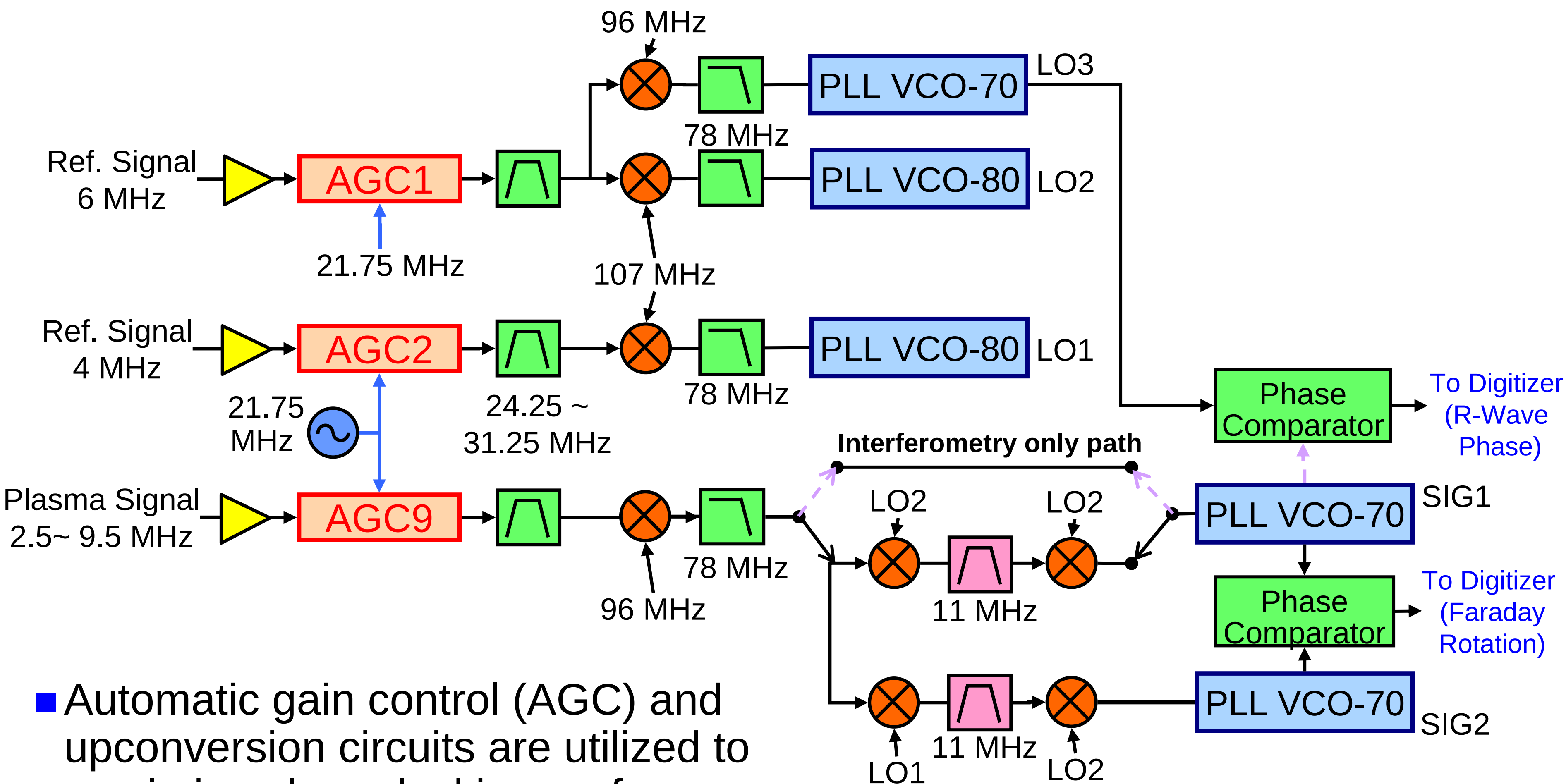
- 2.4 dB variation observed at the output over the 20 dB FIReTIP input signal range
- AGC circuit tested using combined 4.0/6.0 MHz signal corresponding to FIReTIP plasma signals
- Up-converted 25.75 MHz and 27.75 MHz signals as the input to the following PLL circuits (harmonic distortion levels < -42 dBc)

Step 3: Enhanced R- and L-Wave Separation

- For interferometry-only measurements, in which only one of the R- and L-wave components is present, the upconverted plasma signals can be directly fed to phase comparison circuits
- Simultaneous interferometry/polarimetry operation requires that the R- and L-wave components be first separated out and then compared
- Precious system mixes each component to 24.0 MHz and then bandpass filter; measurement bandwidth is limited to that of the filter
- A wide bandwidth filter is required to increase measurement bandwidth, but with sharp band edges for signal selectivity – only available at low frequency (see right)
- Solution is to downconvert the ~70 MHz signals to 11 MHz, bandpass filter, and then upconvert back to ~70 MHz for phase comparison measurements



New IF Electronics Layout



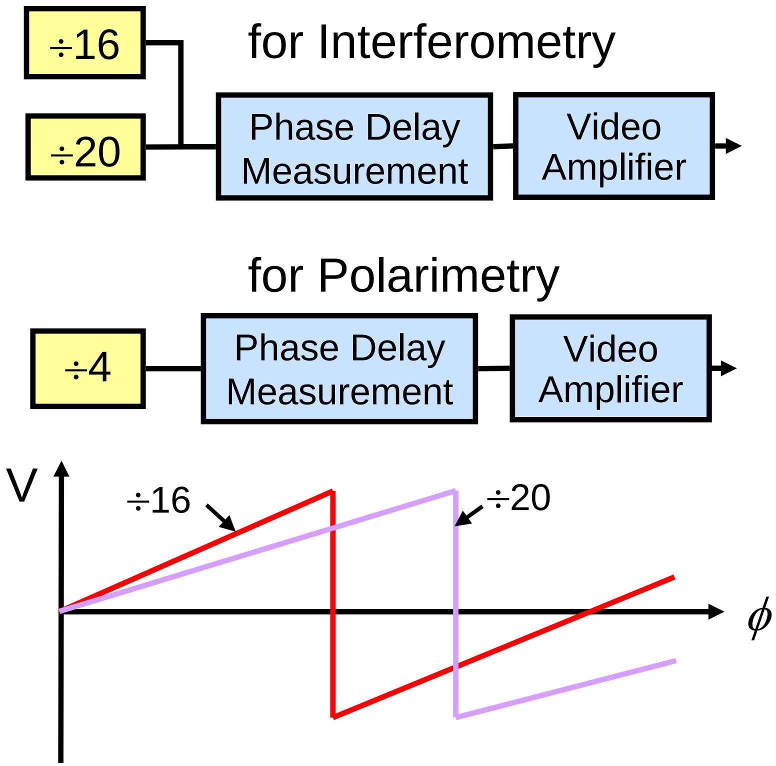
- Automatic gain control (AGC) and upconversion circuits are utilized to maximize phase-locking performance
- Both reference (2) and plasma (7) signals now go through the PLLs at
  - ~70 MHz (reference+plasma), and
  - ~81 MHz (reference only, to separate out R- and L-wave signal components)

Step 4: Phase Comparator Circuits

- Overview of previous approach
  - Analog signals upconverted to 24 MHz, bandpass filtered, and converted into TTL signals using zero-crossing comparators
  - Phase delay measured employing S-R flip flop circuits
  - Interferometer signals employ ÷16 and ÷20 circuits digitized at 1.25 MHz
    ÷16 circuits have input frequency of ~1.5 MHz, output filtered to 330 kHz
    ÷20 circuits have input frequency of ~1.2 MHz, output filtered to 280 kHz
  - Polarimeter signals employ ÷4 circuits digitized at 1.25 MHz and output filtered to 12 kHz
- Overview of new approach
  - Analog signals upconverted to 70 MHz, bandpass filtered (as needed for polarimetry), phase-locked to reduce noise, and converted into TTL signals using either zero-crossing comparators or I-Q mixers
  - Zero crossing phase delay measured employing S-R flip flop circuits
  - Interferometer signals employ pair of ÷8 and I-Q mixer circuits
    - ÷8 circuits are digitized at 1.8 MHz, set 90º apart and output filtered to 1.08 MHz
    - I-Q mixer circuit is digitized at 12.5 MHz and output filtered to 5.6 MHz
  - Polarimeter signals employ the I-Q mixer circuit digitized at 12.5 MHz

Comparison of Phase Comparator Circuits

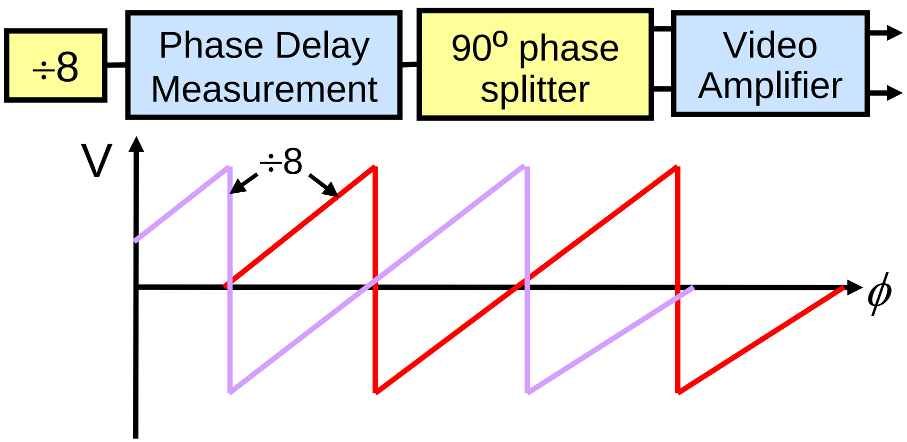
Previous arrangement



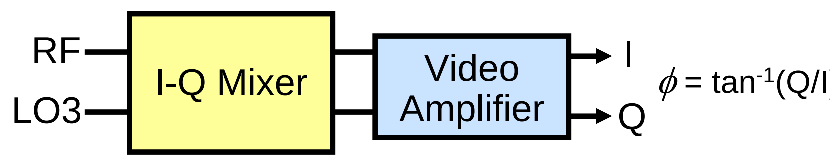
- 24 MHz mixer output signal
- Bandwidth for ÷16 circuit: 330 kHz
- Bandwidth for ÷20 circuit: 280 kHz

Improved arrangement

Narrow- or Wide-band Interferometry

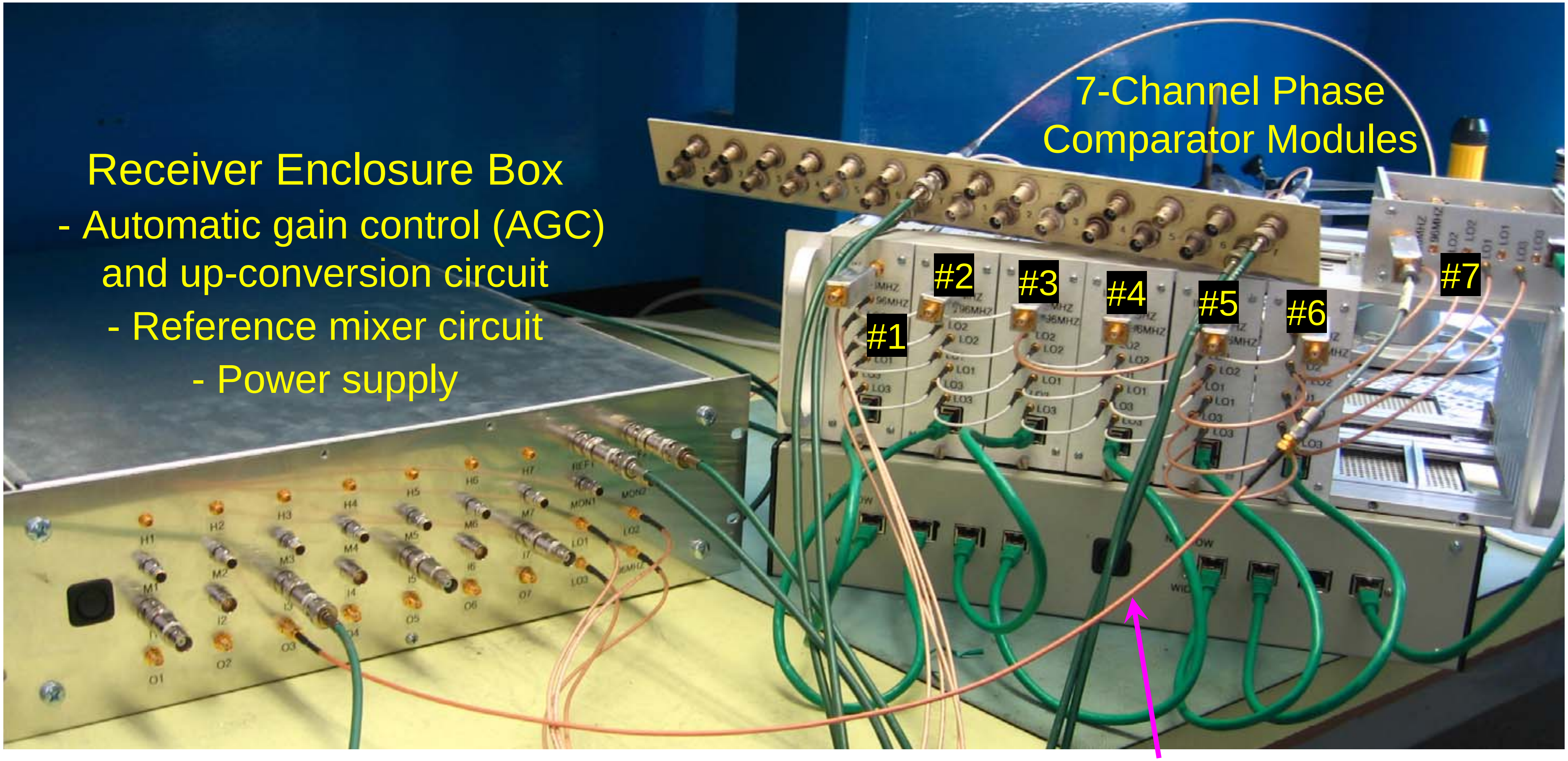


Narrowband Pol. or Wideband Int.



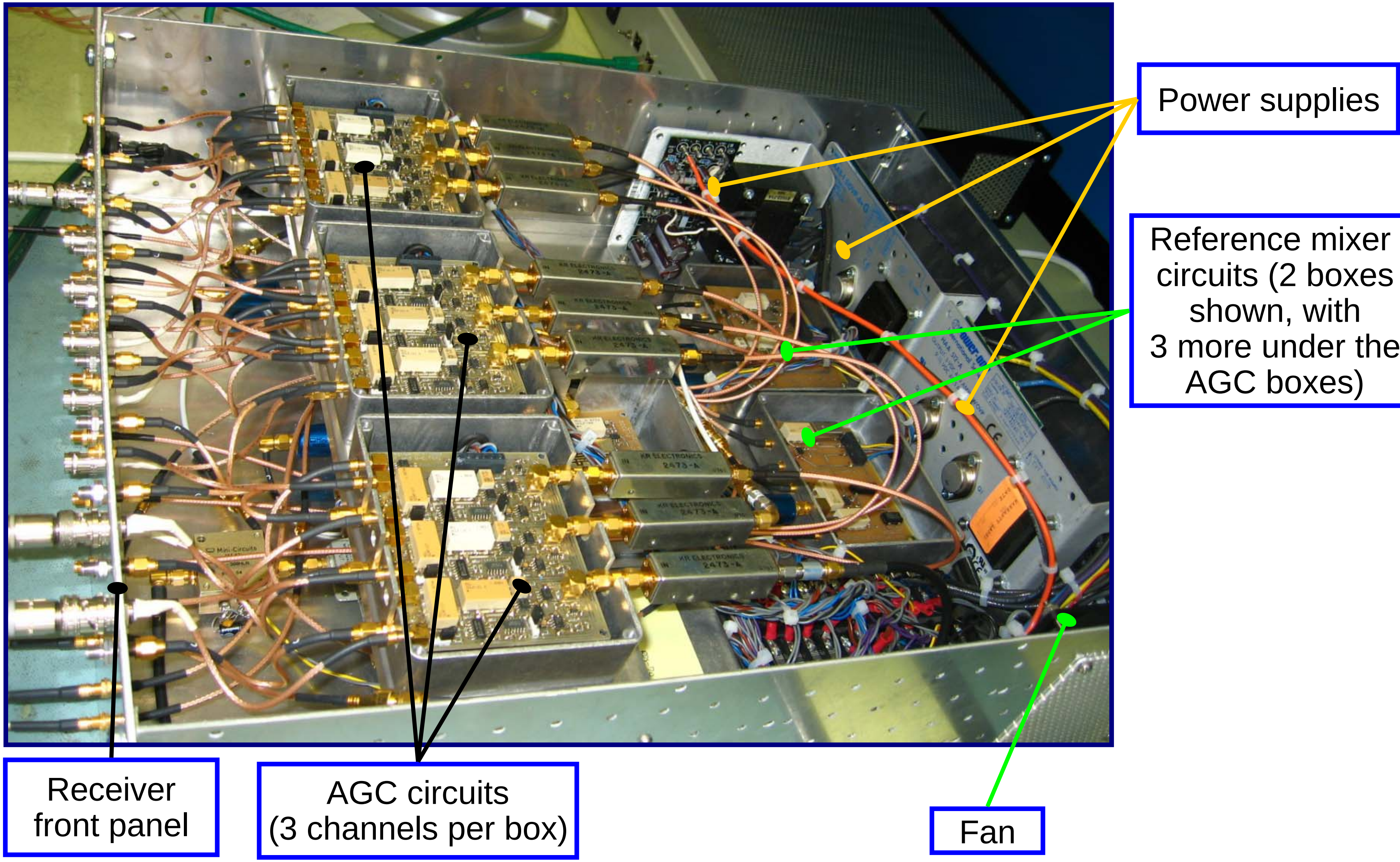
- 70 MHz PLL signal
- Compact 90º phase splitter/I-Q circuit design
- Wideband bandwidth: 4 MHz
- Narrowband bandwidth: 800 kHz

FIReTIP IF Electronics System in Operation



Phase Comparator Power Supply Enclosure Box

Receiver Enclosure Box

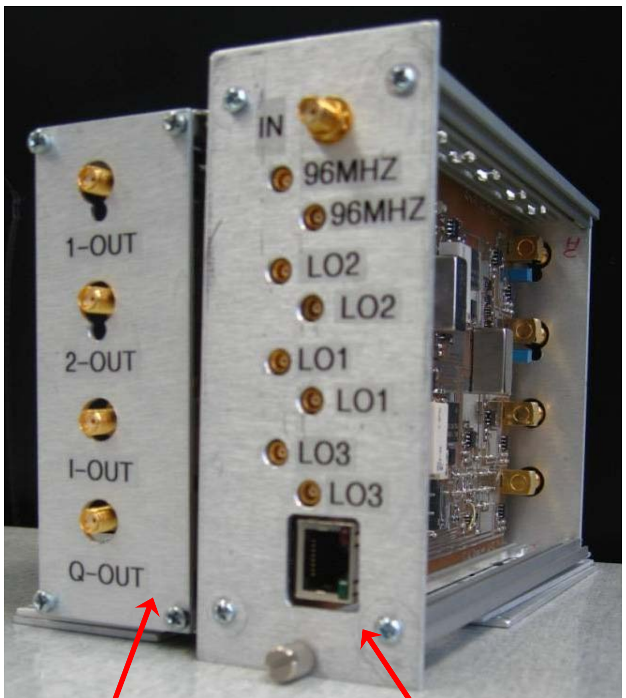


Interferometry/Polarimetry Phase Comparator

PLL and R- and L-wave separation circuits

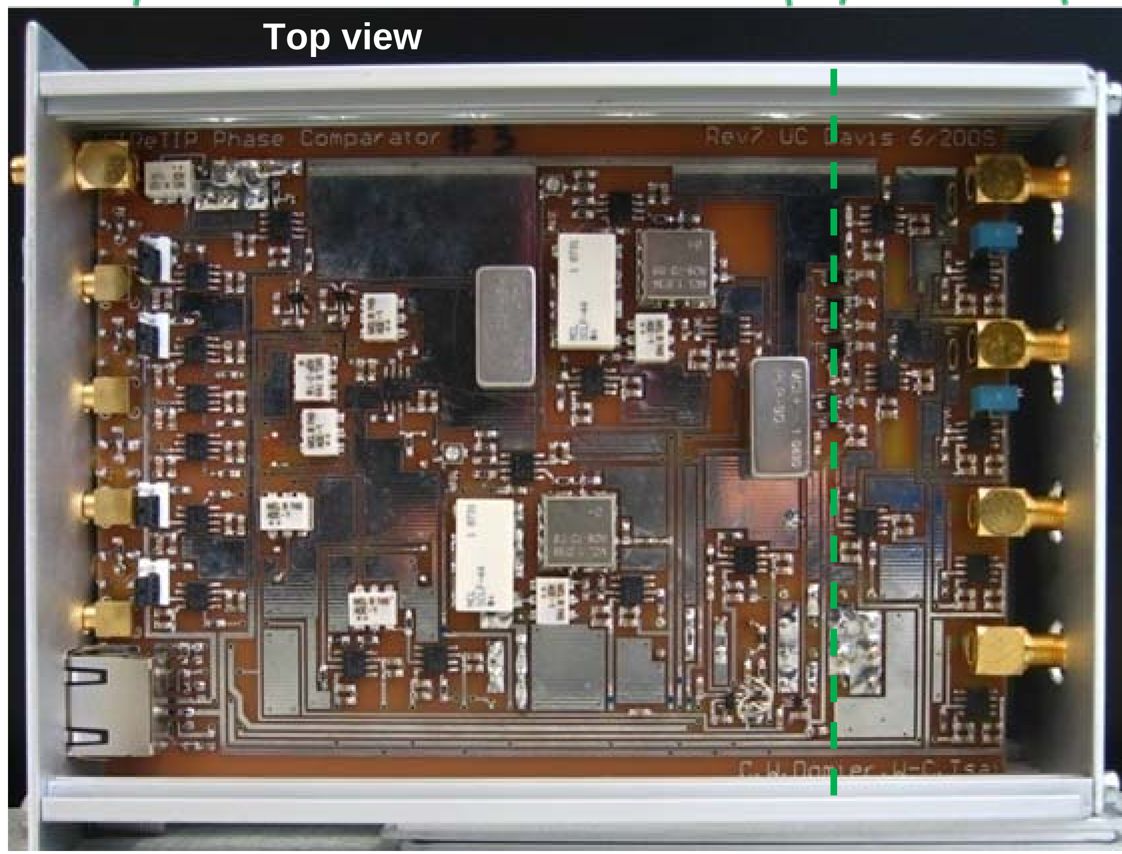
Phase comparator

Single module

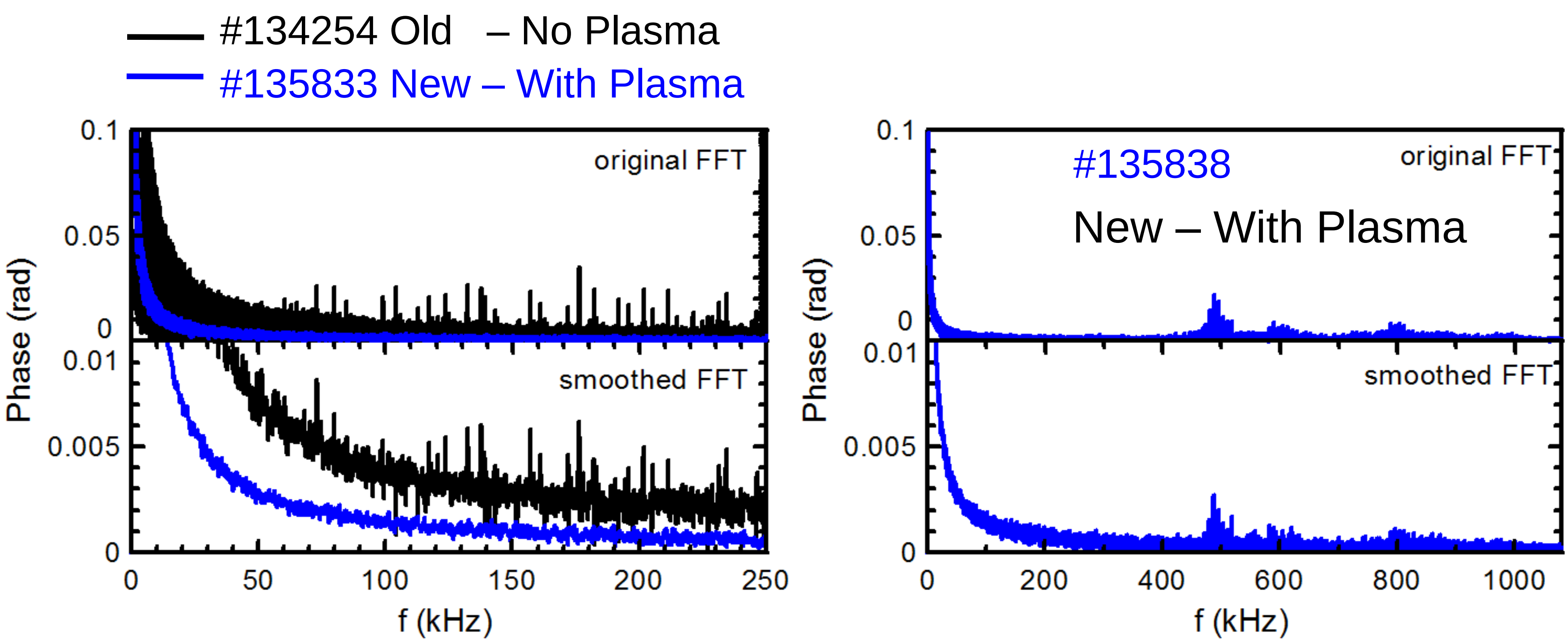


Back side

Front side

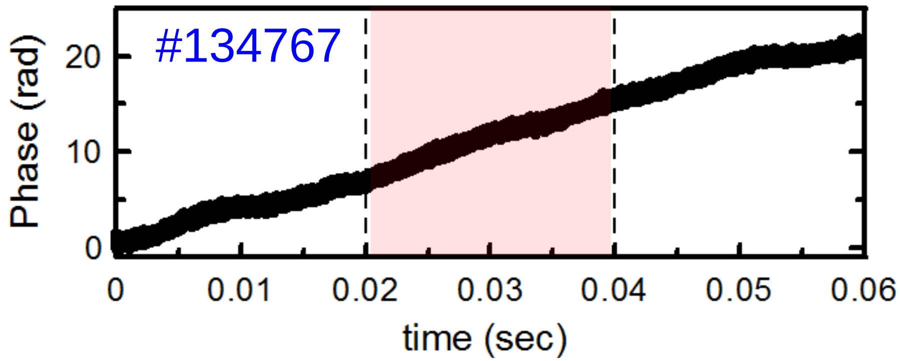


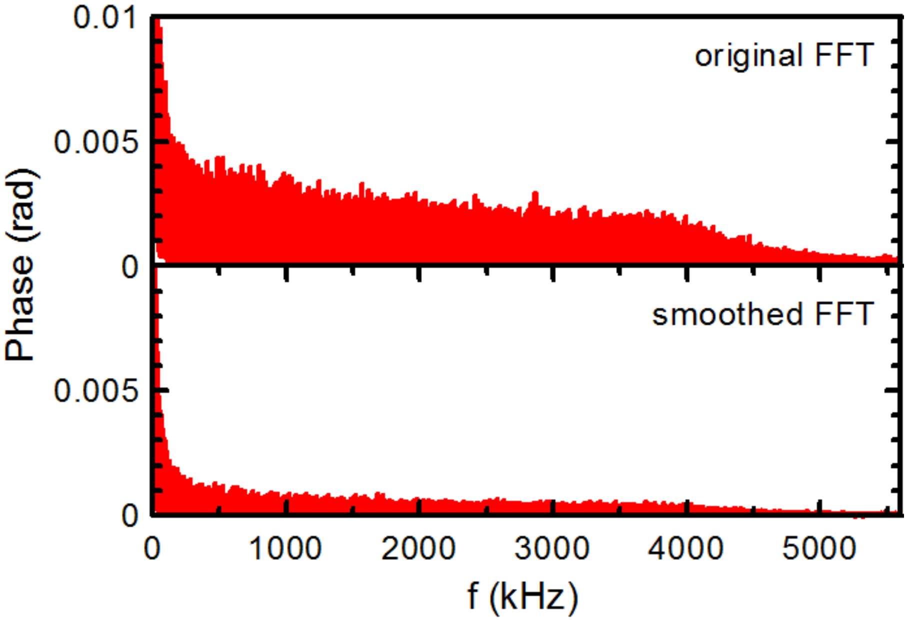
New vs. Old Digital Electronics



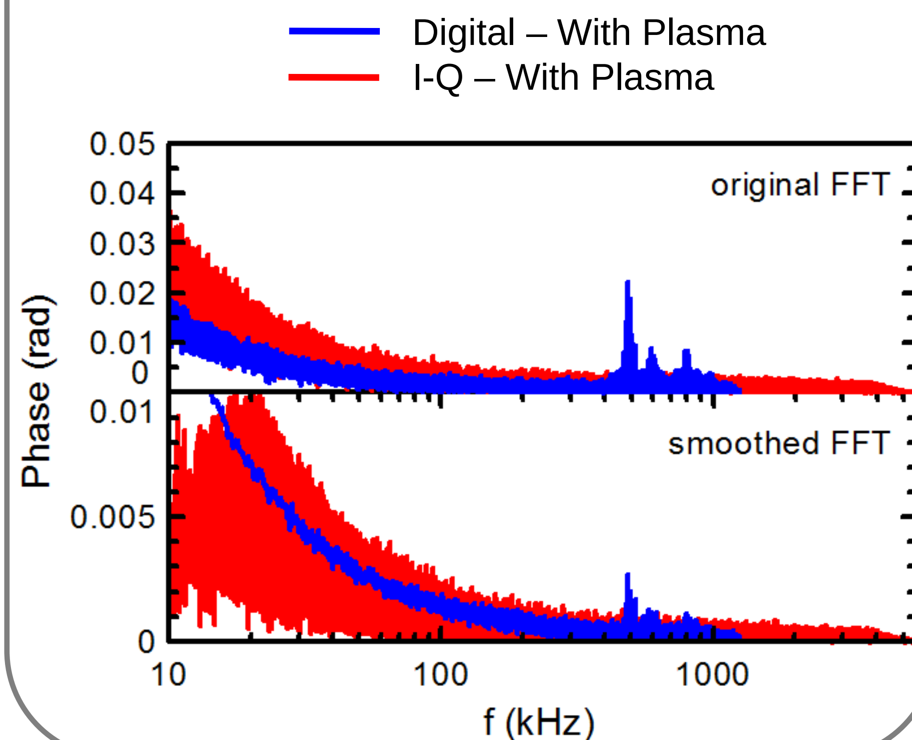
- New digital electronics exhibit a lower noise floor than the old electronics, with significantly higher bandwidth (800 kHz vs. 250 kHz) and higher phase resolution (2X from electronics, and 4X from digitizers)
- New electronics also avoid the large "frequency spikes", thought to result from the use of zero-crossing detectors in the old electronics

New I-Q Electronics Outputs





Noise Spectrum Comparison



- Video bandwidth extends to >4 MHz
- Background noise levels similar to the new digital electronics

Summary and Future Work

- PLL circuits have been designed and fabricated, with considerable improvement in modulation bandwidth and lock-in/tracking ranges
- AGC (and upconversion) circuits have been designed and fabricated to support the new PLL circuits, with only 2.4 dB change in output power observed over a 20 dB range of input signal level
- New circuits have been designed to separate the R- and L-wave signal components (required for polarimetry) with both increased selectivity and increased bandwidth
- New compact digital and I-Q phase comparator circuits have been fabricated for use in high bandwidth FIReTIP phase measurements
- The new wide bandwidth FIReTIP electronics was installed on NSTX in July 2009
- Digital phase comparators with improved phase noise performance now achieve ~800 kHz video bandwidth
- I-Q phase comparators achieve ~4 MHz bandwidth, with similar phase noise performance as digital phase comparators