Progress in Development of Arc Localization Techniques

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Outline

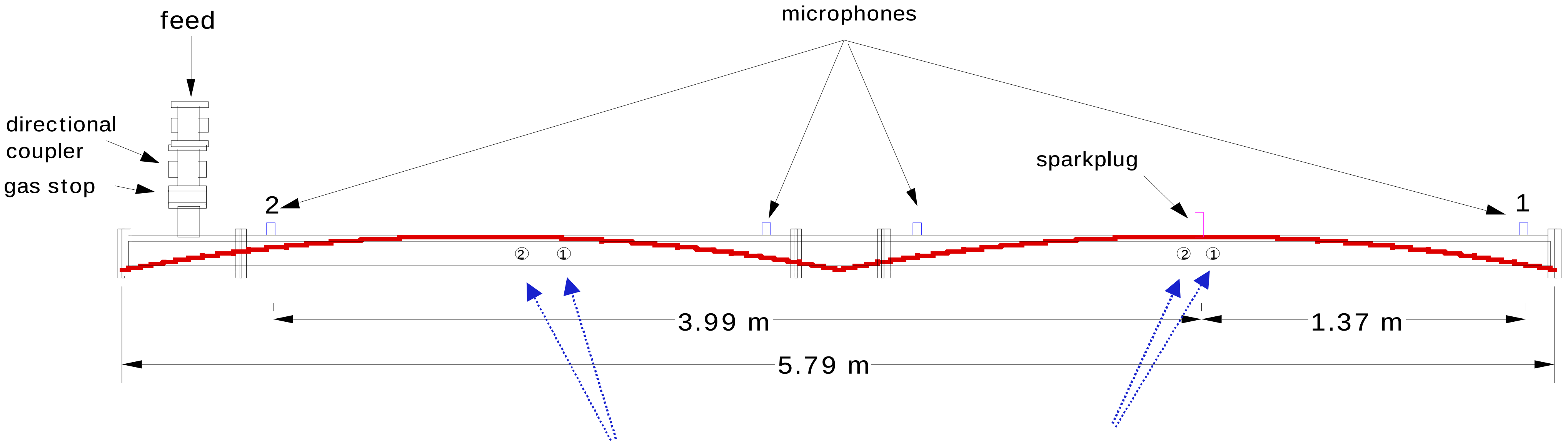
- Arc Localization
  - acoustic
  - RF
- High voltage tester status
- Light ion helicon source

Arc Localization Approach

- In pressurized transmission lines, use microphones to determine arrival times of arc-generated sound waves traveling through the gas
  - Doesn’t work in lines with major obstructions, e.g. solid inner conductor supports
- In vacuum or pressurized lines, measure phase/frequency relationship of reflection coefficient when high frequency diagnostic wave is injected into line
  - use of ratio ρ allows system to respond only to “downstream” reflections (relative to net power flow)
  - Single injection point can be used with multiple detectors for networks having complex configurations
  - High power RF frequency << injected swept frequency << cutoff frequency for 1st higher order mode
  - Requires coupler with large attenuation at frequency of high power RF and high power handling capability

Arc localization / impedance measurement test line

- DIII-D 6” coax test line



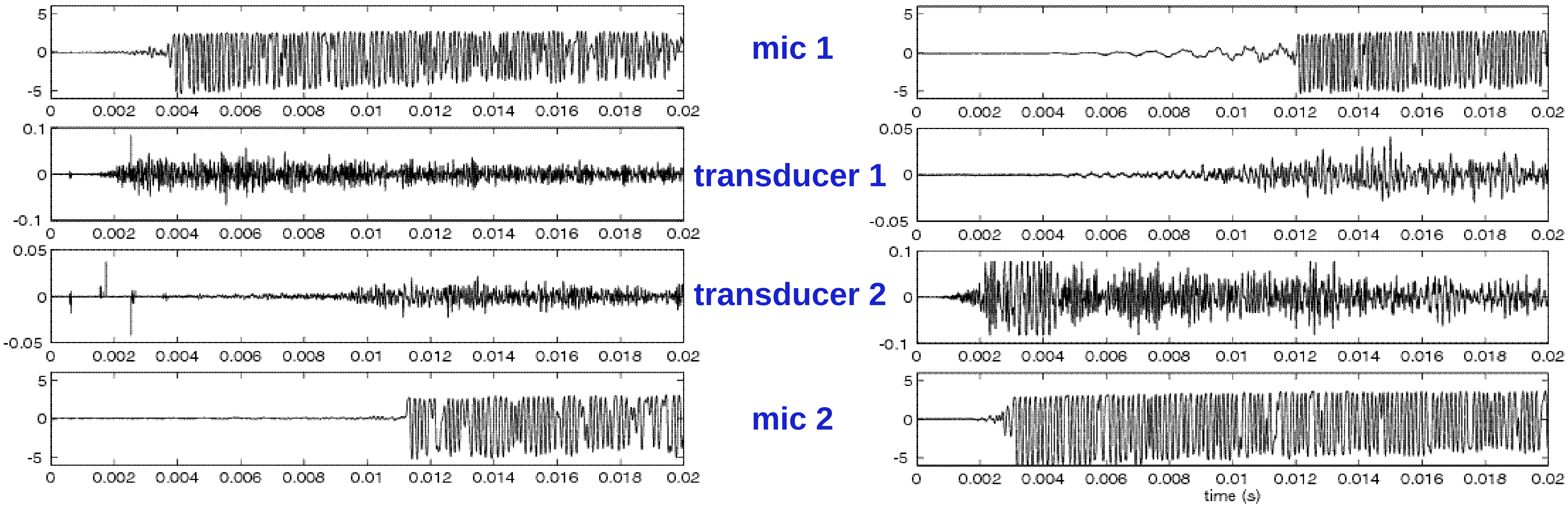
Arc positions determined independently by microphones 1 and 2 (indicated by circles)

- Arcs produced at spark plug and near other voltage maximum (by applying higher power)

Acoustic measurements

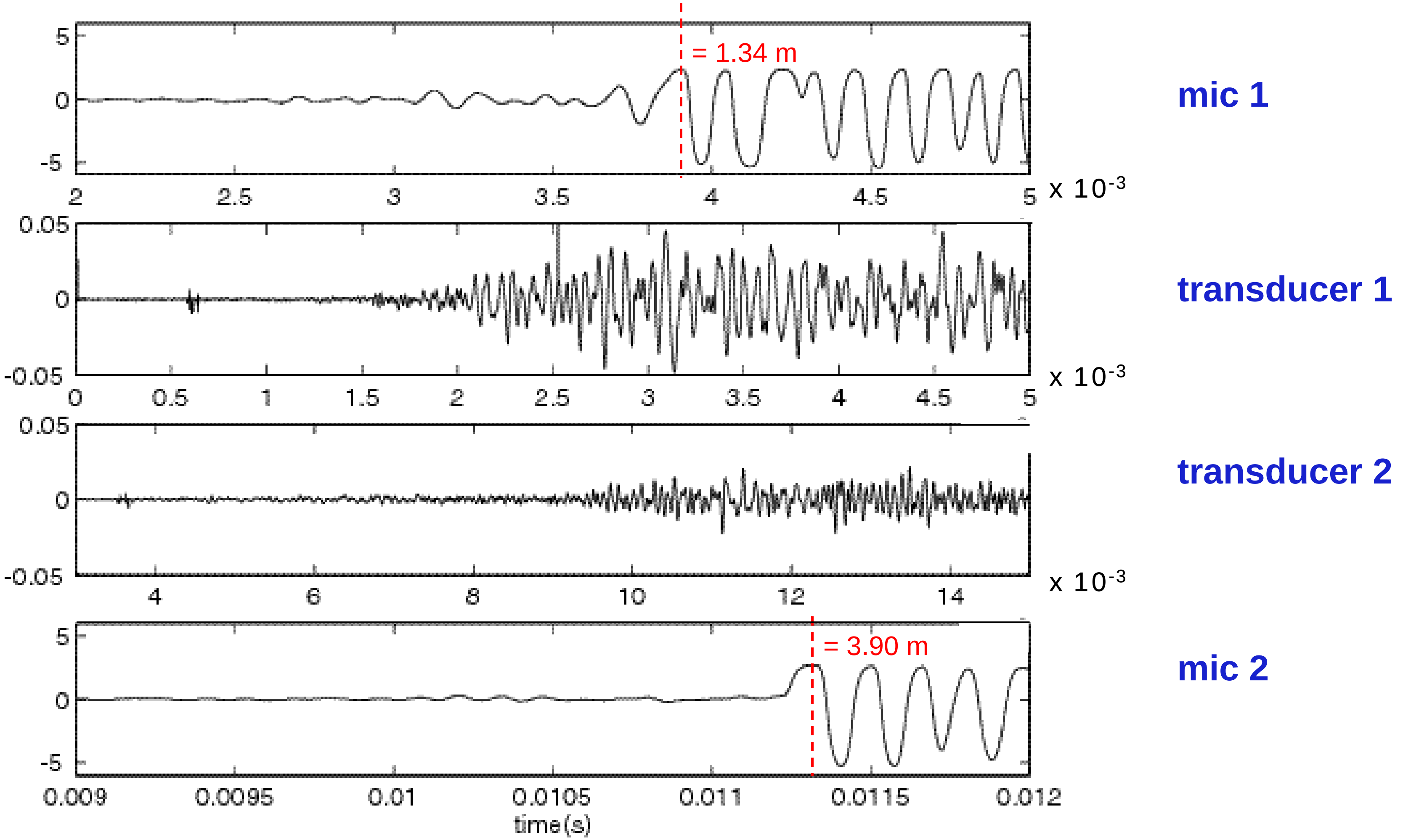
Arc near sparkplug, P = 30 kW

Arc near other voltage maximum, P = 60 kW



- **Microphones measure sound through gas**
- **Transducers measure sound through coax metal walls**

Acoustic measurements with expanded time axis

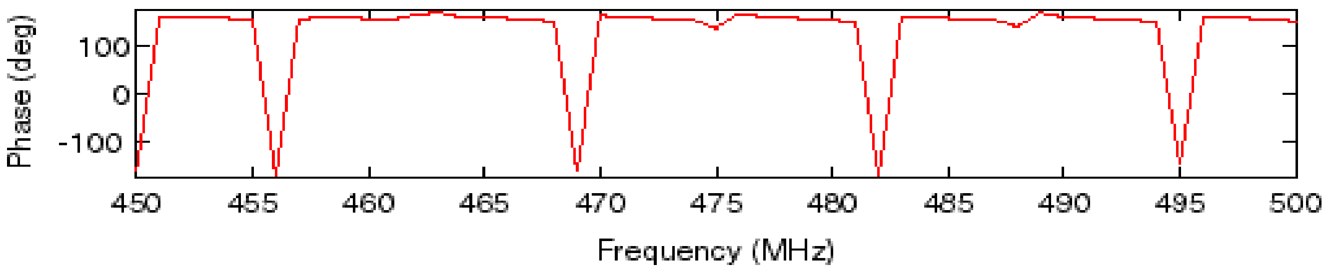


- **T = 0 determined by rise in RF reflected power at feed**

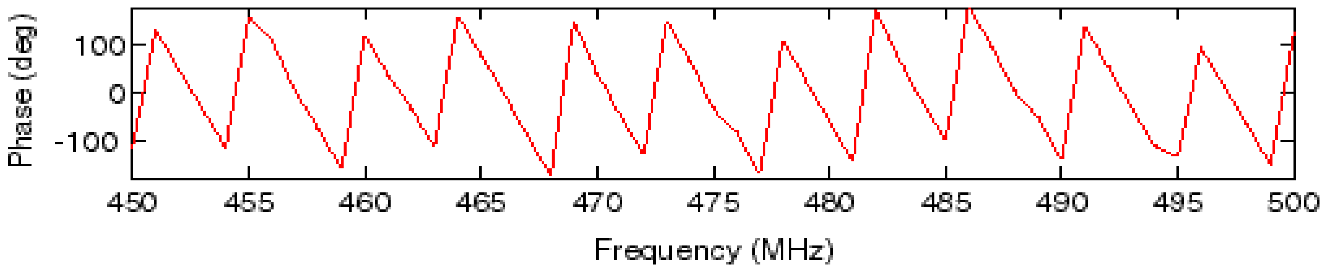
Review of acoustic results

- Arc localized to within ≤ 8 cm in a ~6 m line by measurement of arrival time of sound wave in gas
- High amplitude signals, technique could be used with microphones spaced much further apart than present 5.2 m provided that sound is not attenuated by solid center conductor supports
- Useful results not obtained measuring sound travel in outer conductor

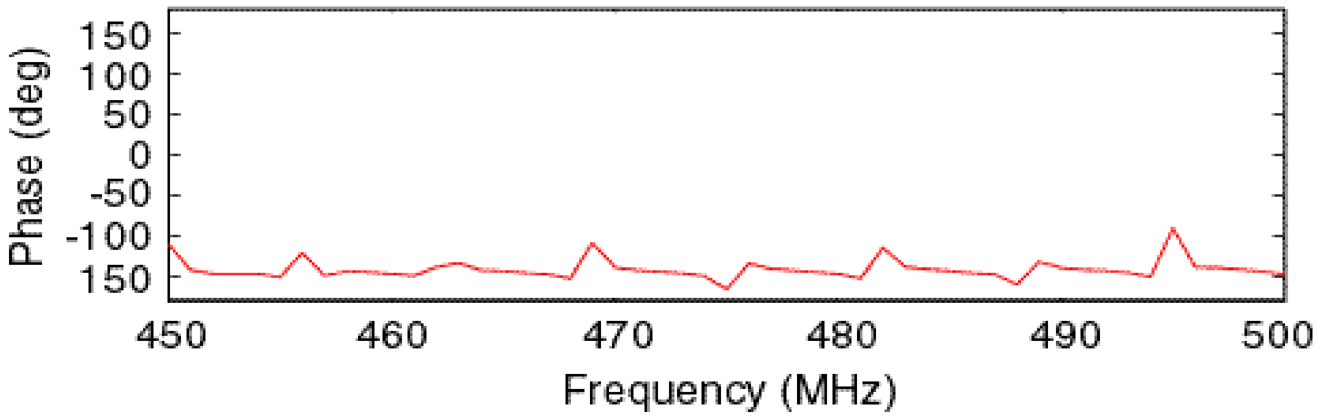
To determine distance to arc, reflection coefficient phase of a high frequency diagnostic wave is measured while frequency is swept, electrical length added to make phase again stationary with frequency



Phase at arc



Phase at directional coupler

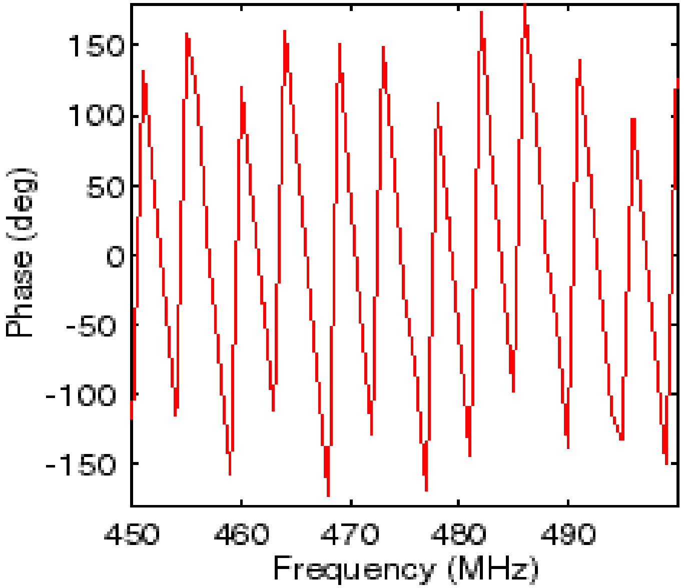


Phase at directional coupler
with 2ω/c×d subtracted off,
d = distance to arc

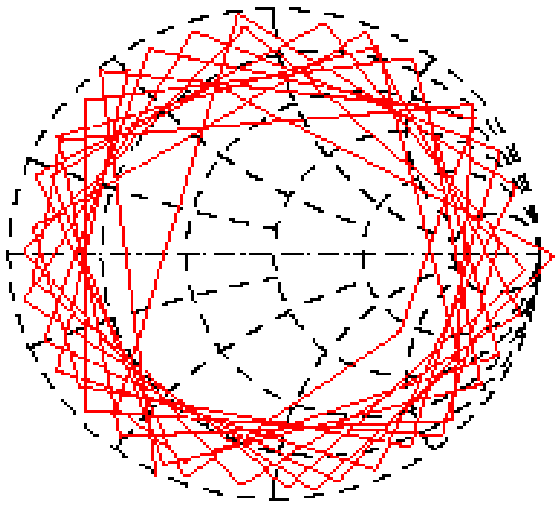
To determine distance to arc, the reflection coefficient phase is first measured as the frequency is swept

- Reflection coefficient measured 33.6 m towards generator from arc for L_{arc} = 3 nH

Reflection coefficient phase



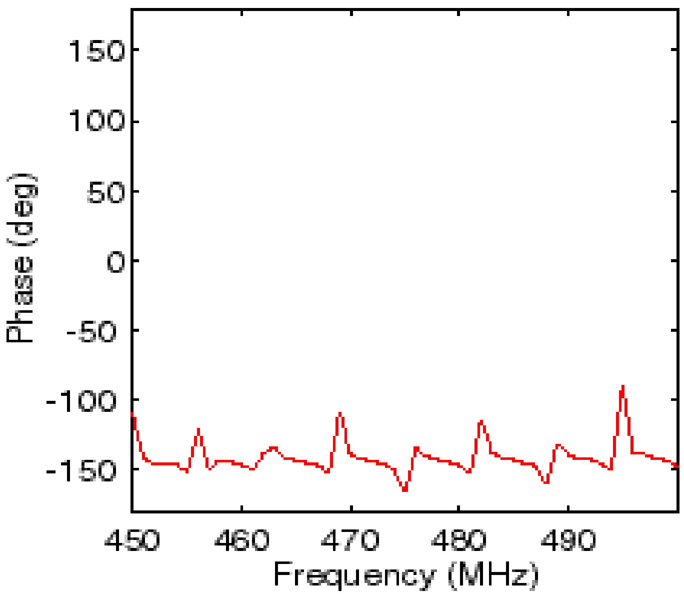
Polar (Smith chart) plot of reflection coefficient



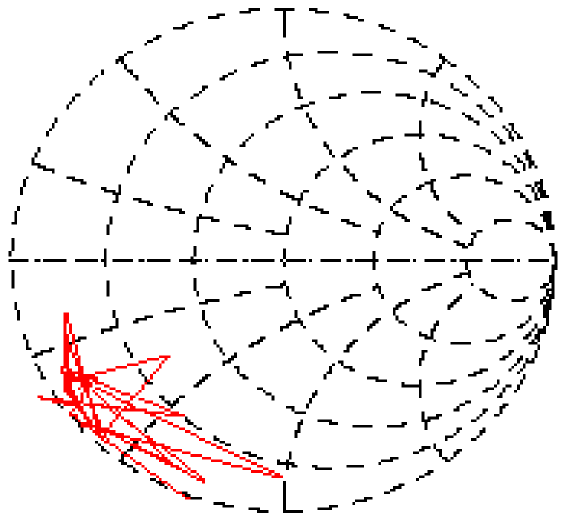
The distance to the arc is determined by subtracting an electrical length *l* which minimizes the variation of the reflection coefficient angle with frequency

- $\rho' = \rho\, e^{2j\beta l}$ where
  - ρ is the original and ρ' the transformed reflection coefficient
  - $\beta = 2\pi f / v_\phi$ where *f* is the frequency and v_ϕ is the phase velocity (= *c* for TEM modes)
- In this example *l* = 33.65 m gives best result - actual distance to arc in model is 33.60 m

Phase of ρ'



Smith chart plot of ρ'



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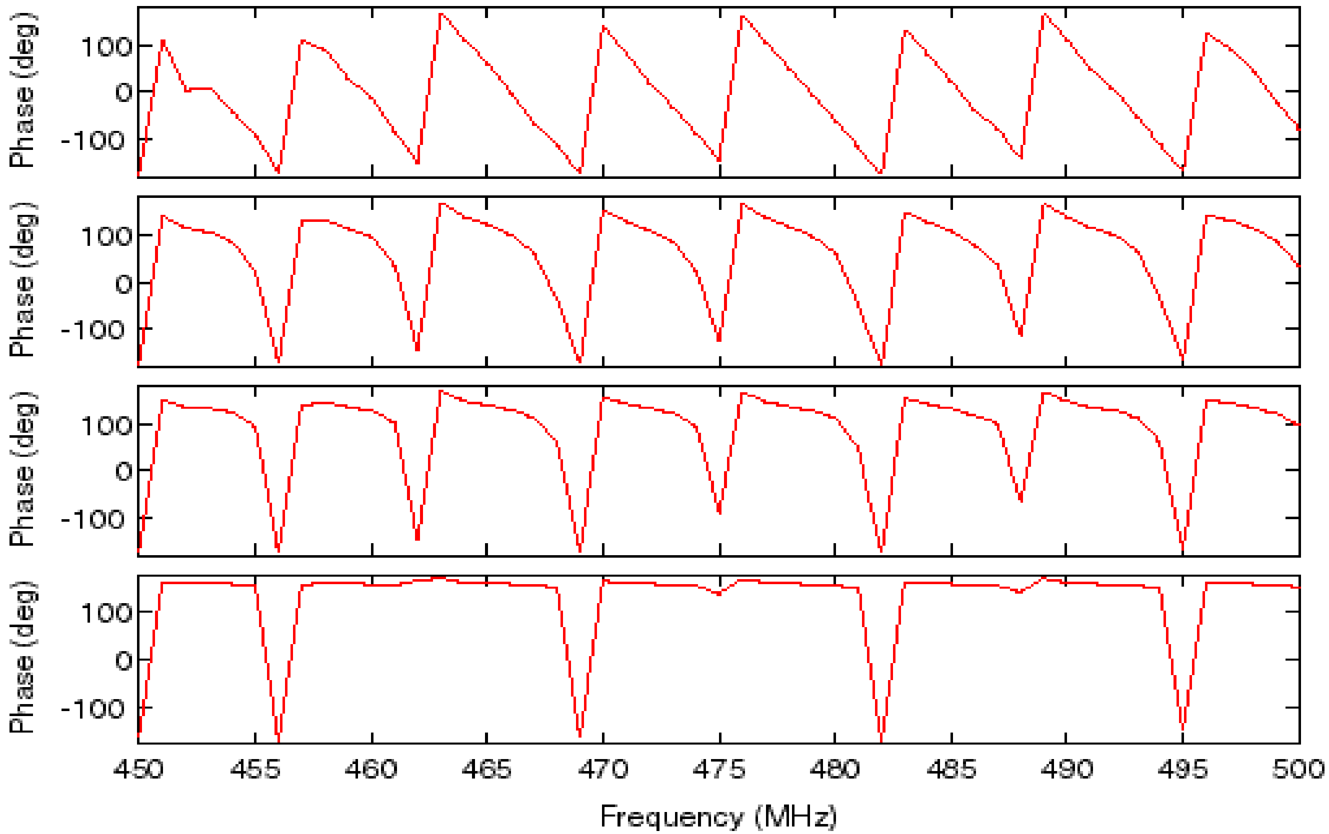
High inductance arcs have a reduced influence on the reflection coefficient phase

- Phase of reflection coefficient (= $V_{reflected}$ / $V_{forward}$) measured directly on the generator side of the arc location



$L_{arc} = \infty$

L_{arc} = 14 nH

L_{arc} = 8 nH

L_{arc} = 3 nH

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Use of baseline data restores sensitivity to arc location

Baseline Subtraction:

$$\rho'_{b=} = \rho_b e^{2\beta l}, \rho'_{t=} = \rho_t e^{2\beta l}$$

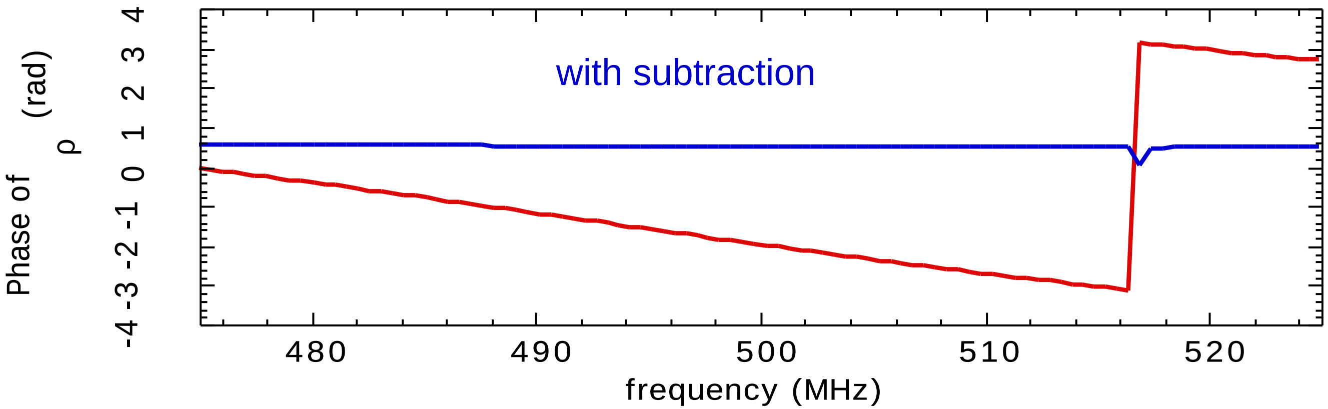
$$y_b = \frac{1-\rho_b}{1+\rho_b}, y_t = \frac{1-\rho_t}{1+\rho_t}$$

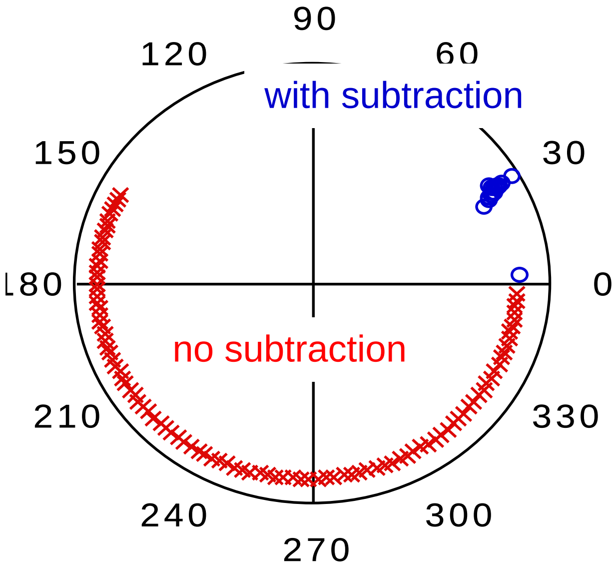
$$y_a = y_t - y_b$$

$$\rho_a = \frac{1-y_a}{1+y_a}$$

subscripts:

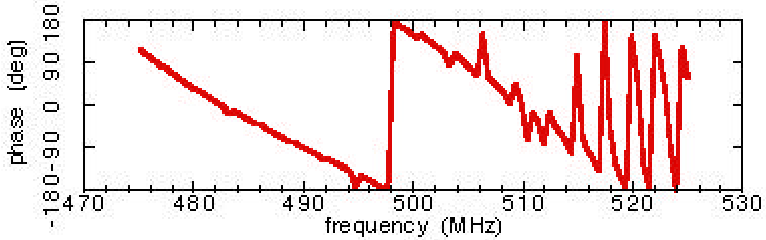
b=baseline
t=total
a=arc



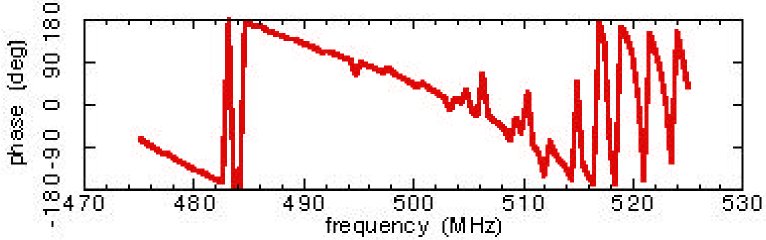


Baseline subtraction also helps eliminate "spurious" phase shifts caused by transmission line resonances

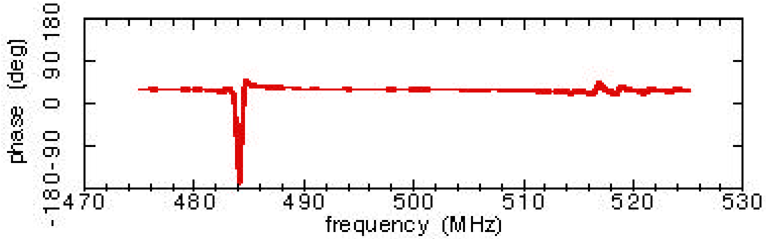
Baseline subtraction also reduces spurious phase shifts due to transmission line resonances produced by parallel connections on the load side of the measurement point. At the right, the reflection coefficient is shown for a 30 nH arc in a 5.7 m line with a second 50 m line connected in parallel between the measurement point and arc.



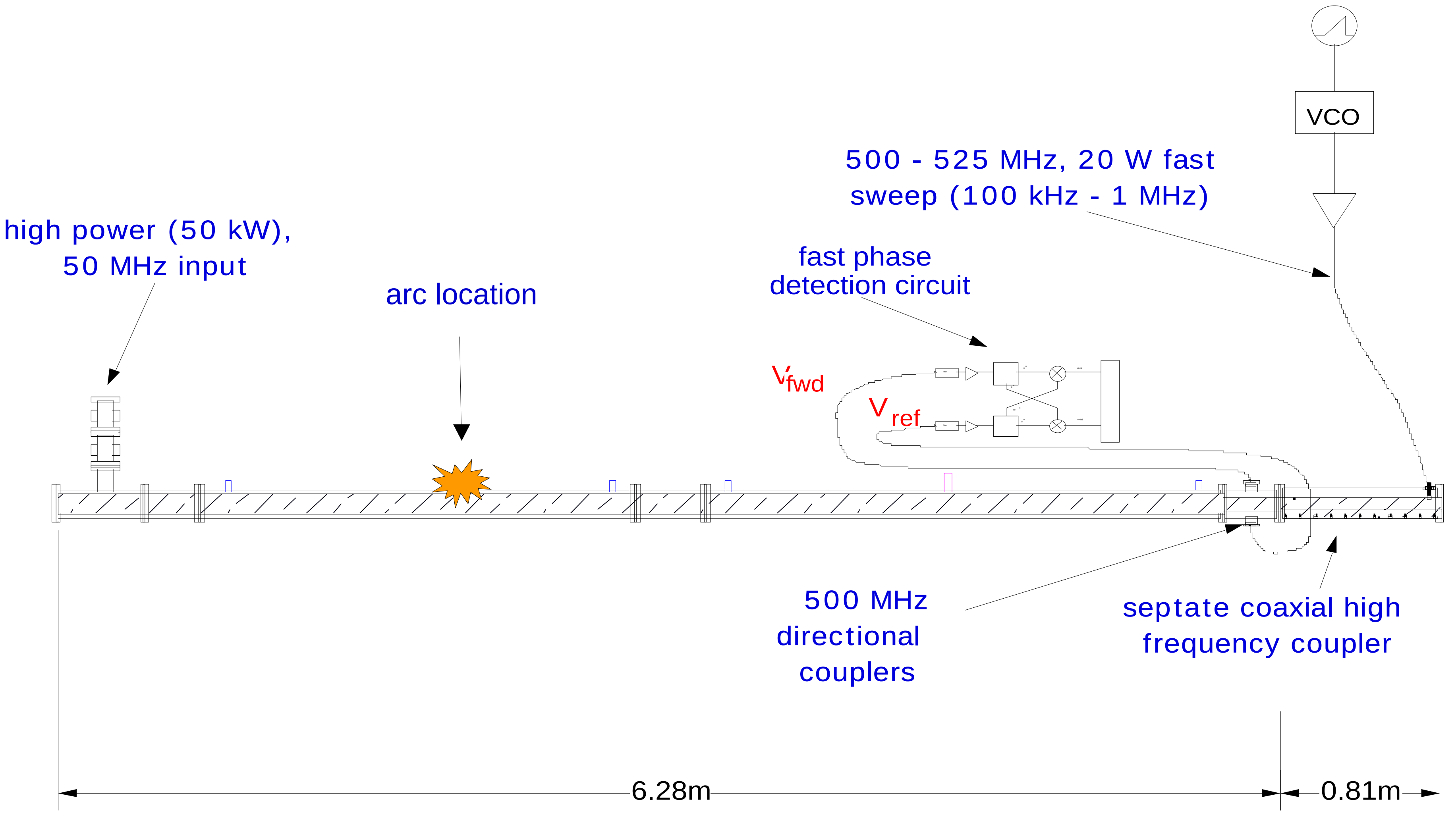
When the reflection coefficient phase is shifted by an electrical length d equal to the distance to the arc according to $\phi' = \phi + 2\omega / c \times d$, rapid phase variations due to the resonances caused by the 50 m line are seen in addition to the residual phase resulting from the high arc impedance.



With baseline subtraction, most of the phase variations caused by the 50 m line resonances as well as that due to the high arc impedance are eliminated.



Swept frequency arc localization test rig



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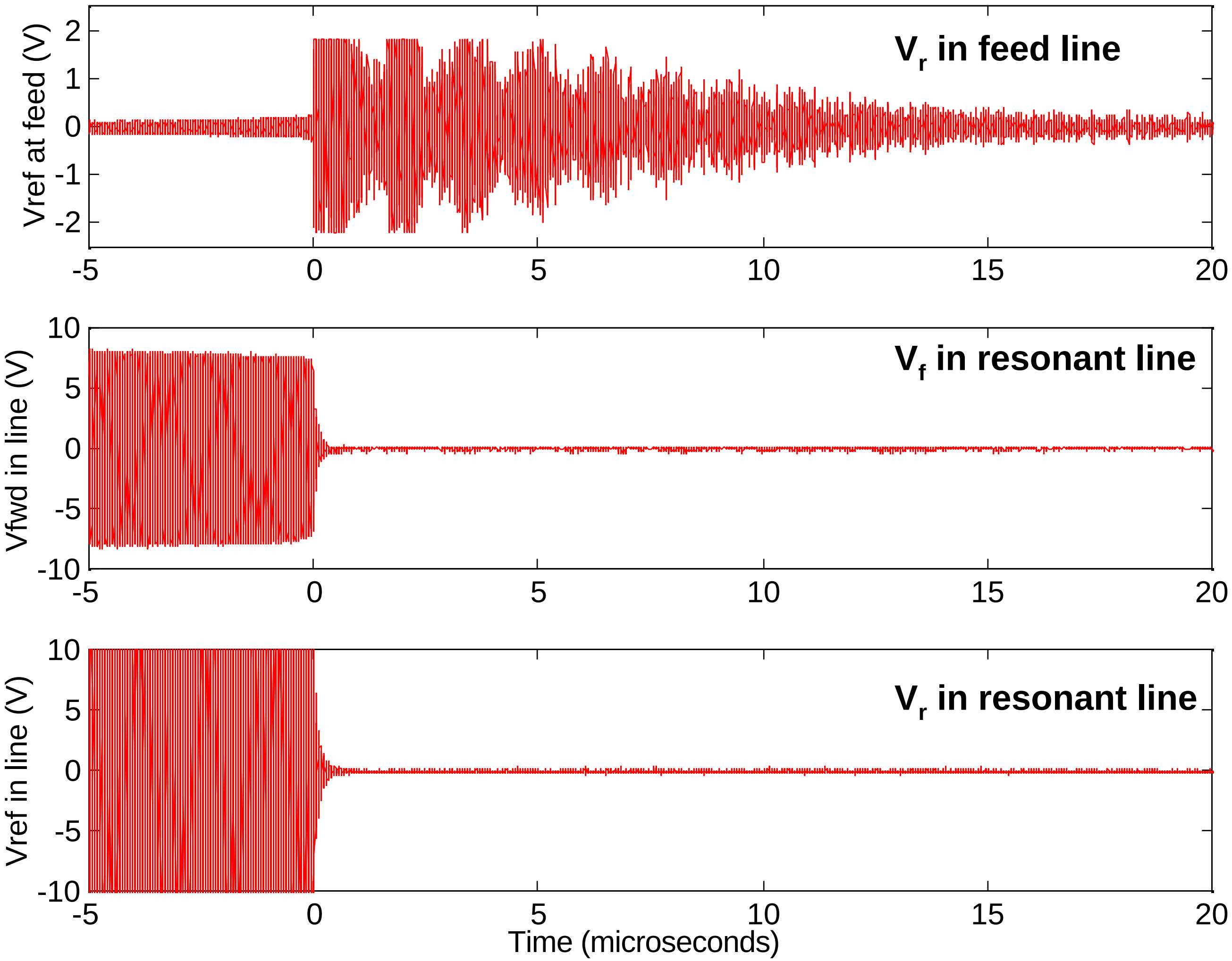
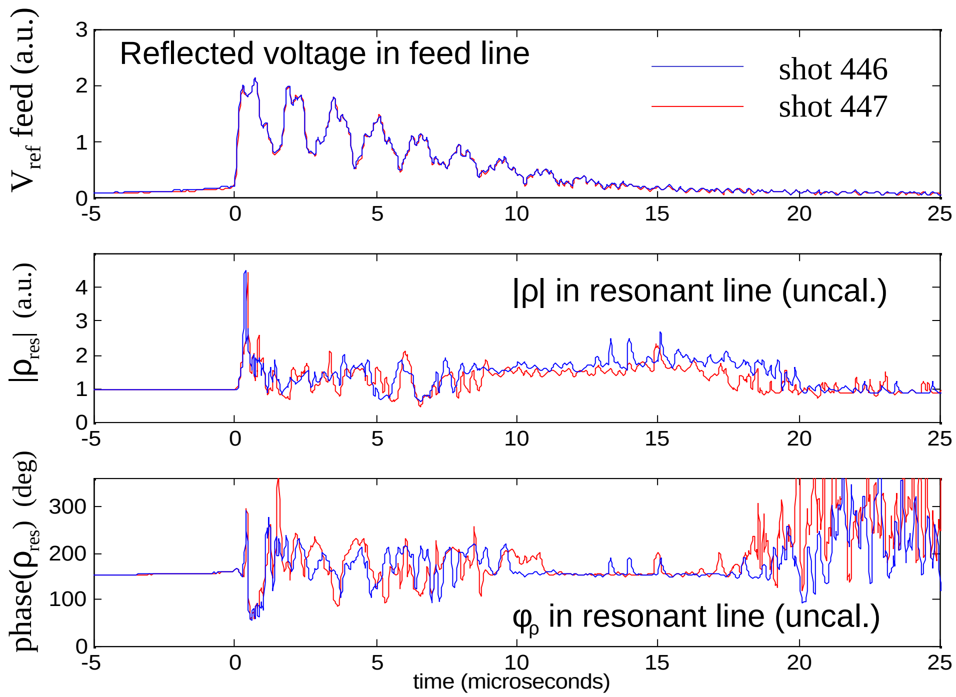
Raw arc data



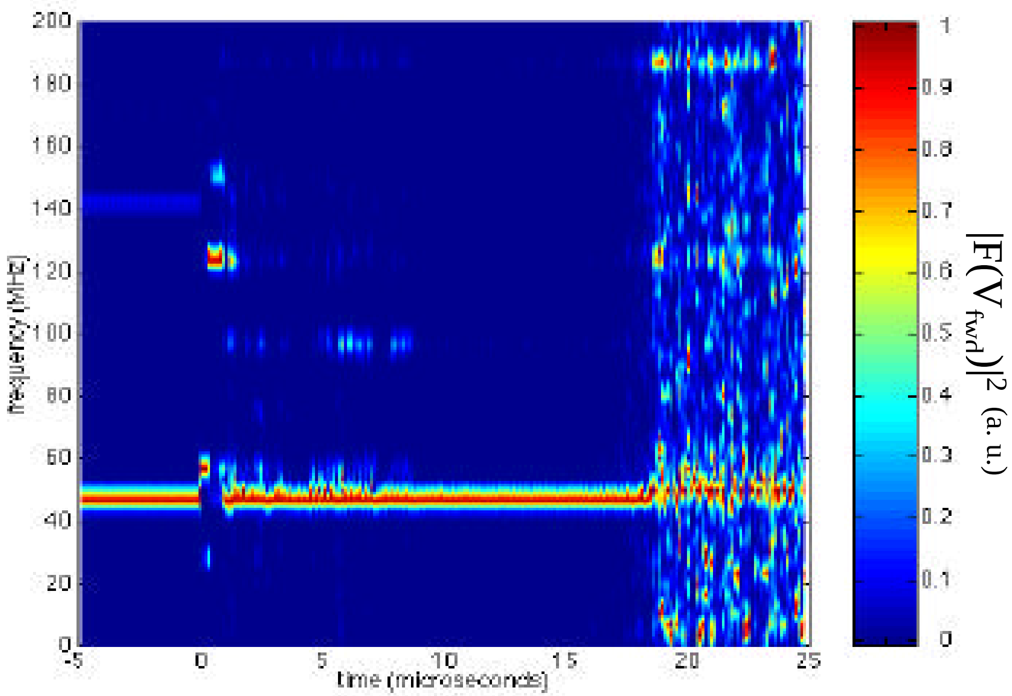
- Voltages in resonant line drop sharply, but remain at finite amplitude, with measurable phase and frequency for > 20 μs

RF measurements: A repeatable ~1μs transient is followed by 9-10 μs of less stable behavior

Arc parameters in feedline and resonant line

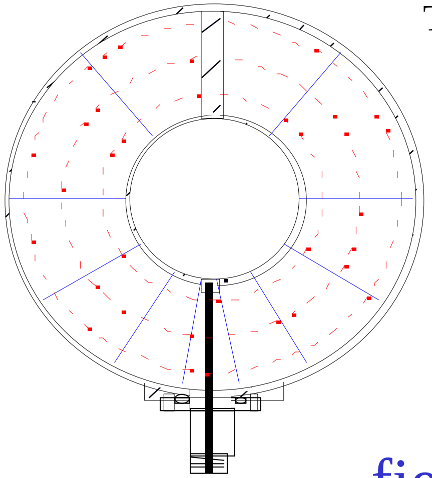


Running Fourier transform of fwd pwr in resonant line



- Two shots shown to indicate reproducibility
- f and φ return to original values after ~ 10 μs, but |ρ| does not

Fields, Cutoff Frequencies, and attenuation in septate coupler



TE_{10} mode approximate fields

electric

magnetic

fields

$$H_z \quad \cos\frac{\phi}{2}\left[J_{1/2}(k_c\rho)-\frac{J'_{1/2}(k_c a)}{Y'_{1/2}(k_c a)}Y_{1/2}(k_c\rho)\right]\sin(\beta z)$$

$$E_\rho \quad \frac{1}{k_c^{\,2}\rho}\sin\frac{\phi}{2}\left[J_{1/2}(k_c\rho)-\frac{J'_{1/2}(k_c a)}{Y'_{1/2}(k_c a)}Y_{1/2}(k_c\rho)\right]\sin(\beta z)$$

$$E_\phi \quad \frac{\omega}{k_c^{\,2}}\cos\frac{\phi}{2}\left[k_c J'_{1/2}(k_c\rho)-\frac{J'_{1/2}(k_c a)}{Y'_{1/2}(k_c a)}k_c Y'_{1/2}(k_c\rho)\right]\sin(\beta z)$$

$$H_\rho \quad \frac{\beta}{k_c^{\,2}}\cos\frac{\phi}{2}\left[k_c J'_{1/2}(k_c\rho)-\frac{J'_{1/2}(k_c a)}{Y'_{1/2}(k_c a)}k_c Y'_{1/2}(k_c\rho)\right]\cos(\beta z)$$

$$H_\phi \quad \frac{\beta}{k_c^{\,2}\rho}\sin\frac{\phi}{2}\left[J_{1/2}(k_c\rho)-\frac{J'_{1/2}(k_c a)}{Y'_{1/2}(k_c a)}Y_{1/2}(k_c\rho)\right]\cos(\beta z)$$

cutoff wavenumber

$$\left(2k_c a-\tan(k_c a)\right)\left(1+2k_c b\tan(k_c b)\right)-\left(2k_c b-\tan(k_c b)\right)\left(1+2k_c a\tan(k_c a)\right)=0$$

cutoff frequencies

50Ω: 447.9 MHz

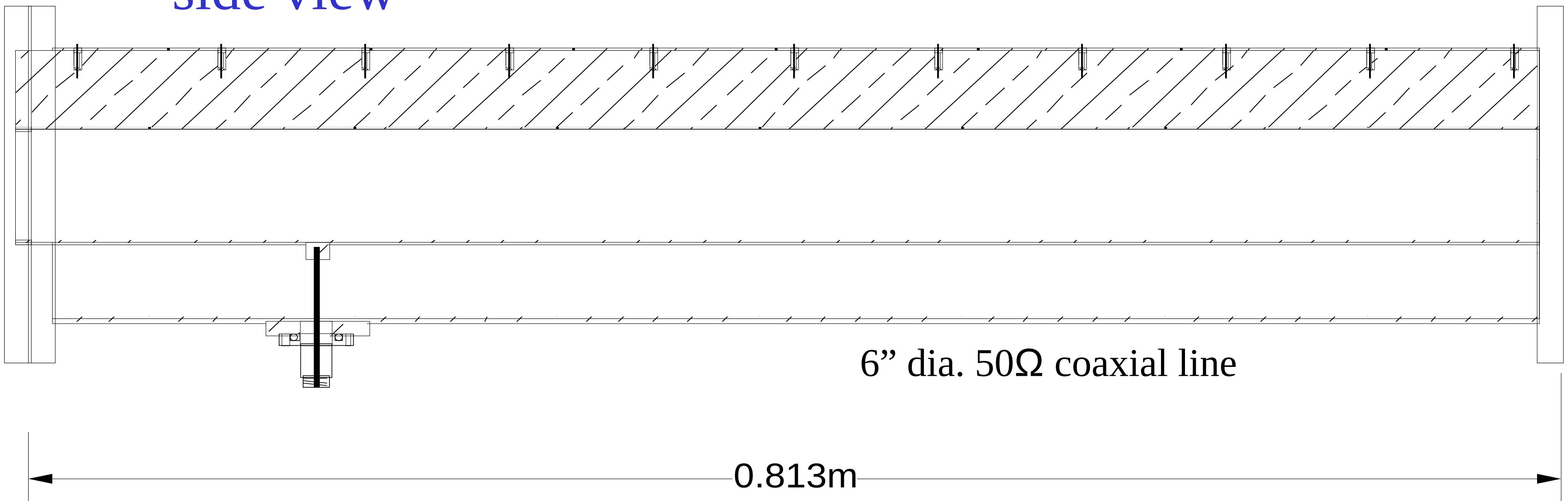
25.7Ω: 382.0 MHz

attenuation - 50Ω, 66 cm @ 50 MHz

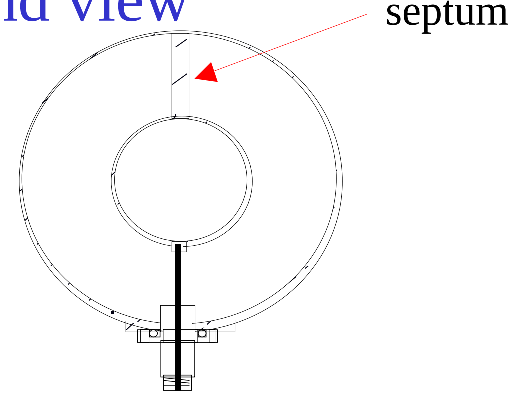
52.1 dB

A septate transmission line is an efficient high frequency diplexer

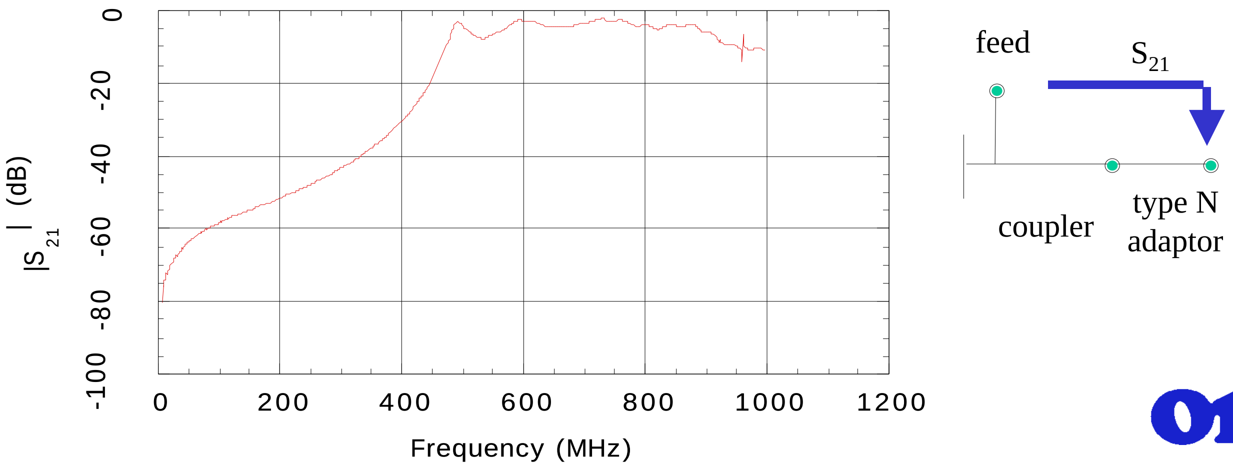
side view



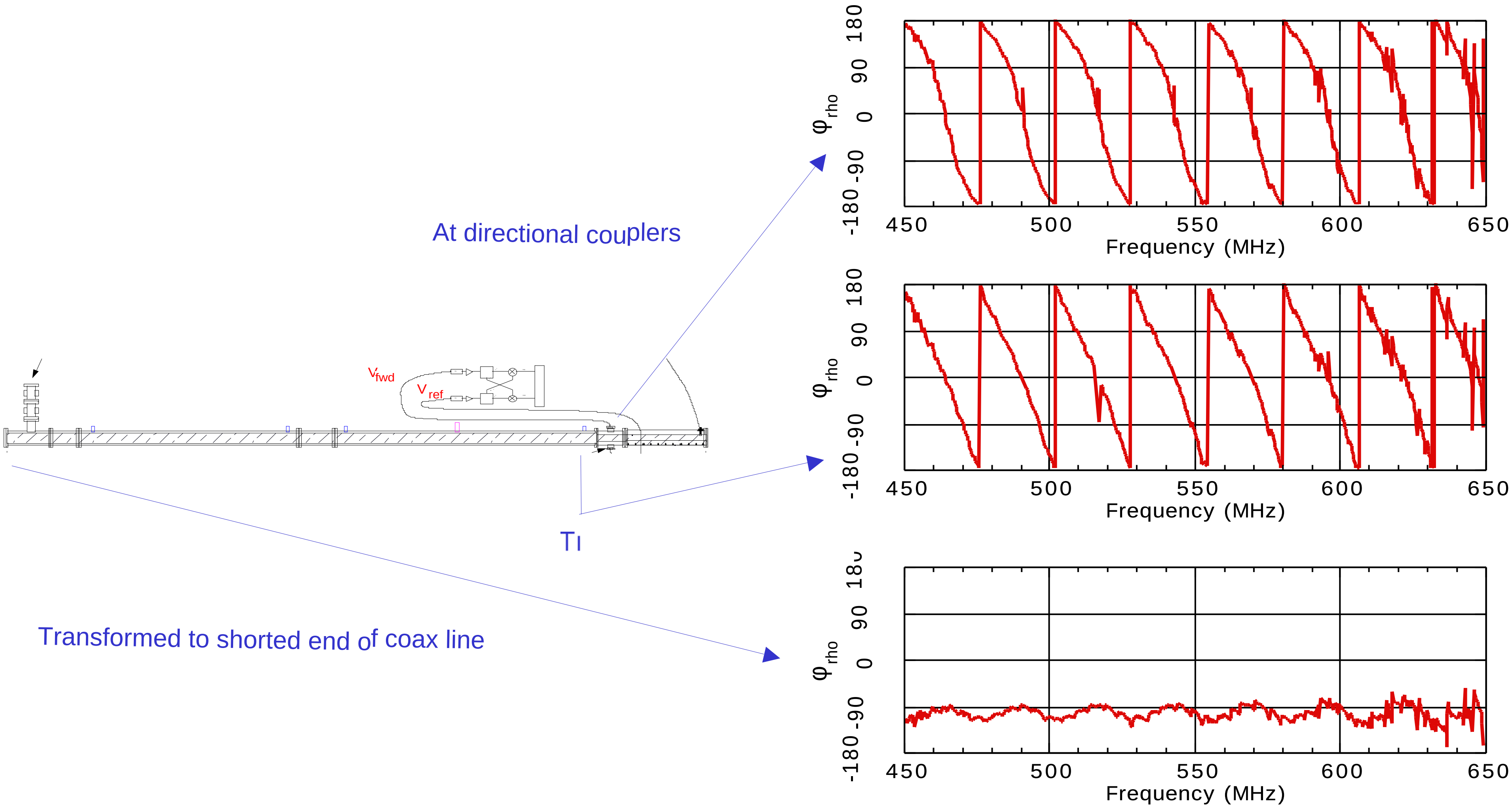
end view



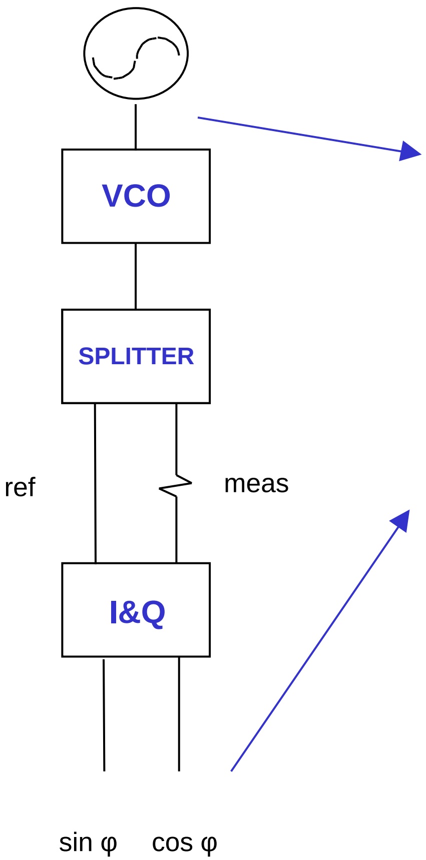
transmission coefficient

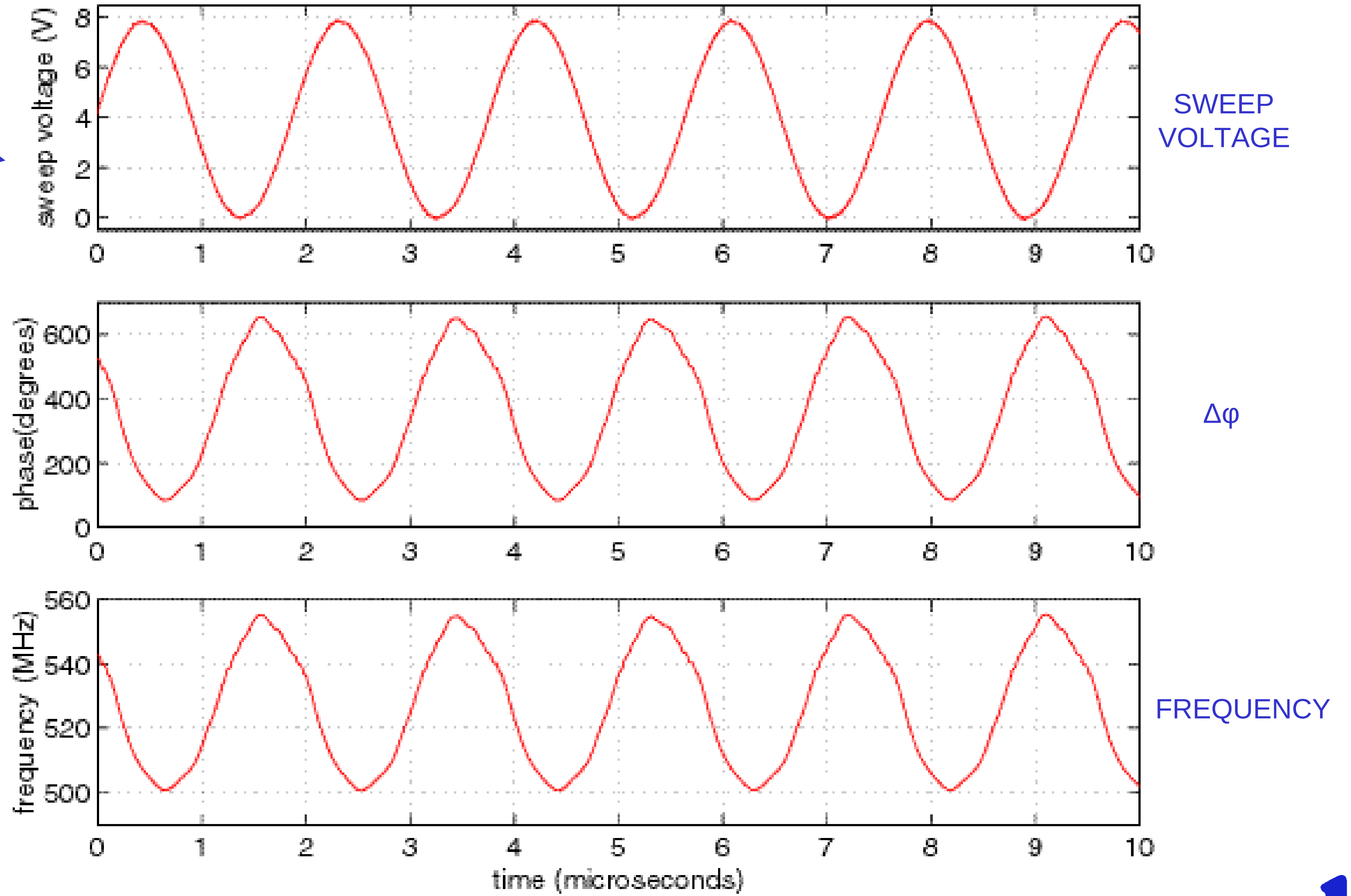


Test of 500 MHz sweep



A voltage controlled oscillator has been used to produce frequency sweeps with a period of ~ 1μs





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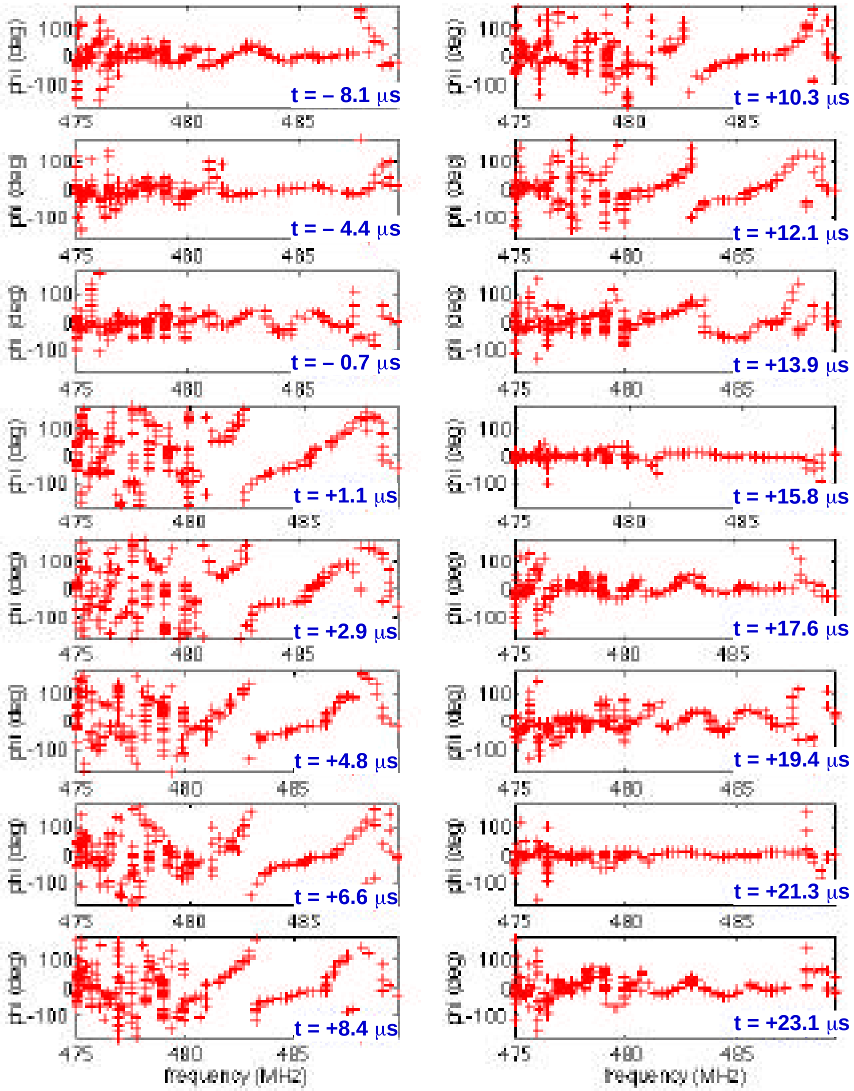
Example of analyzed data shows frequency dependent phase shift during arc

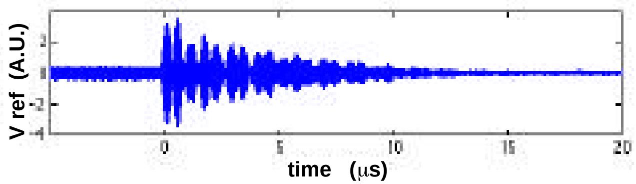
arc begins here →



- Data graphed is difference between phase during sweep centered at the times shown and phase measured during a baseline sweep obtained before breakdown occurs
- A reproducible, clear increase in this phase difference with frequency is observed between t = 1.1 ms and t = 12.1 ms
- The graphs for times before the arc and late times afterwards are nearly identical, and show no systematic change in phase with frequency in comparison to baseline data

These initial results indicate:

- Arcs cause a measurable change in reflection coefficient phase as a function of frequency over some frequency range
- Measurement of the phase of the diagnostic signal can be made successfully in the presence of high rf power levels at the driving frequency
- Electrical characteristics of the arc are sufficiently stable over short (several microsecond) periods to allow useful measurements to be made



- Reflected voltage magnitude in feedline vs time for above graphs

Summary

- Measurement of RF parameters during arcs without high frequency injection show frequency shift during arcs
- A high power, high frequency coupler diagnostic wave coupler has been successfully designed, built and tested - provides –5 dB coupling at 500 - 900 MHz, – 63 dB coupling at 50 MHz
- Measured transmission line length using swept frequency technique at high frequency
- Baseline subtraction technique developed which increases sensitivity to high inductance arcs and improves accuracy in the presence of resonances produced by transmission line elements connected in parallel on the load side of the arc location
- Initial measurements show phase shift during arc which is not seen before arc. Proves that arc produces measurable change in diagnostic wave phase shift, and that measurement is insensitive to the high power low frequency RF producing the arc