Reactivity Measurements in MUSE-4 Using Noise Analysis Techniques

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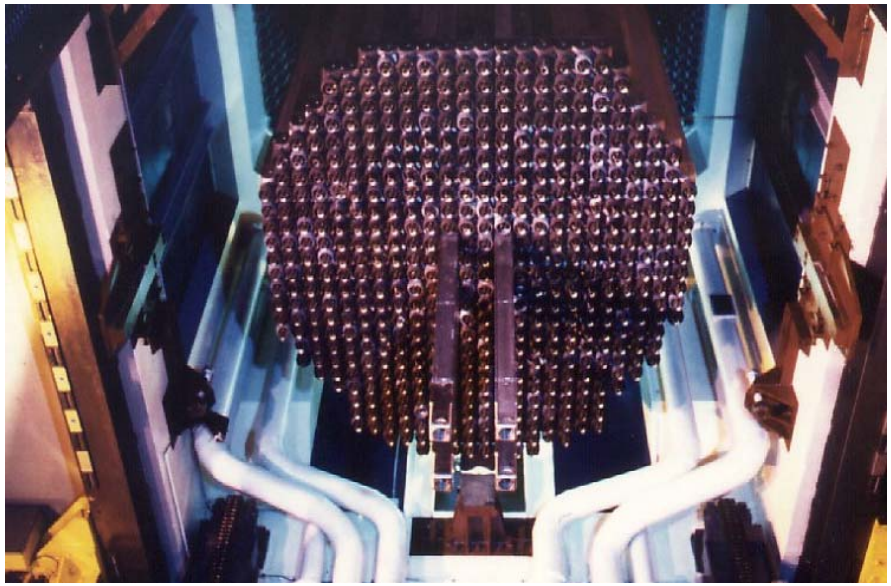
In cooperation with CEA, CNRS, and other MUSE partners

MUSE-4 Project

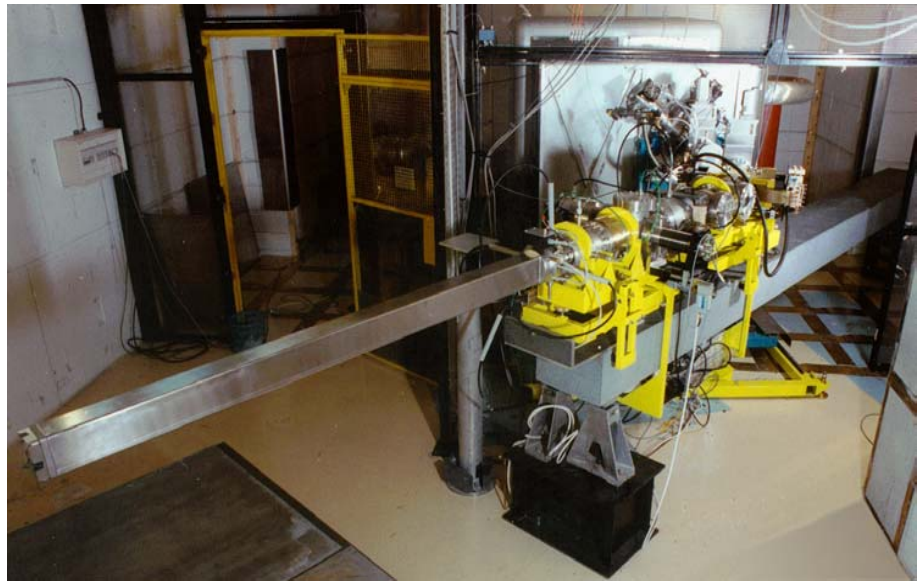
Objectives:

- Understanding of the behavior of a subcritical reactor core driven by an external neutron source
- Development of experimental techniques for the control and the monitoring of a future ADS
- Definition of reference tools (nuclear data, codes, …)
- Follow-up of MUSE-3 (1998) that used a commercial neutron generator (14 MeV, 2.10^8 n/s) in four configurations (critical, -500, -1000, -1500 pcm)
- Located at CEA, Cadarache (F)

MUSE-4 Project

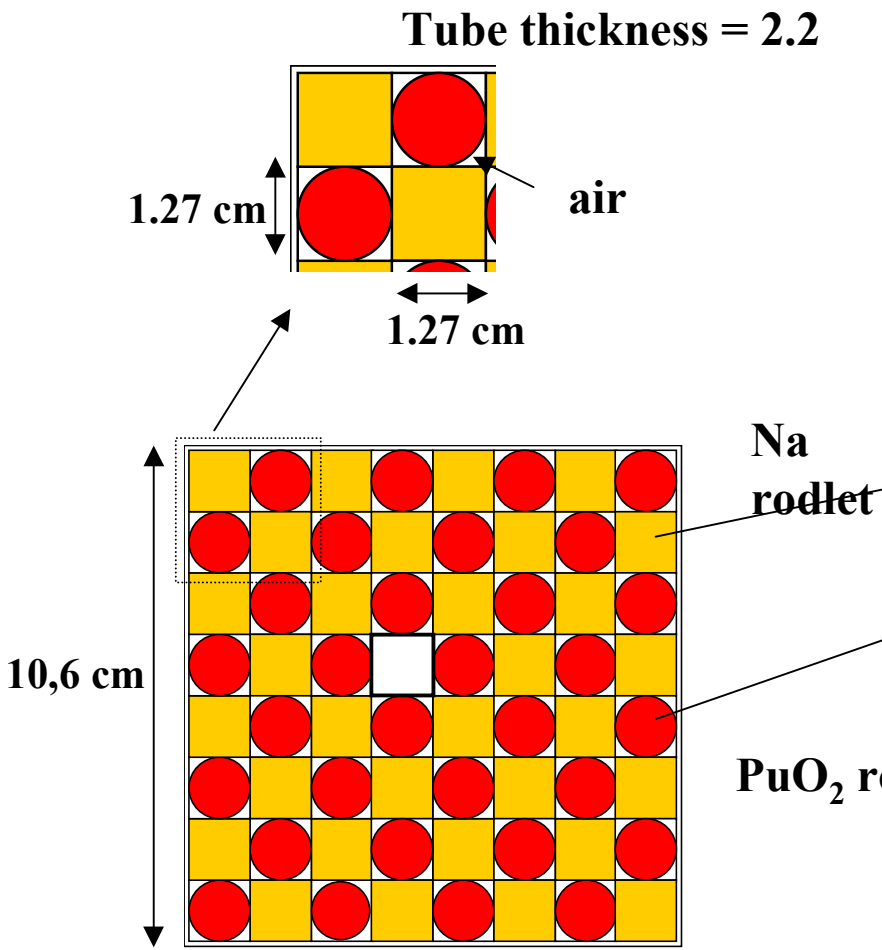


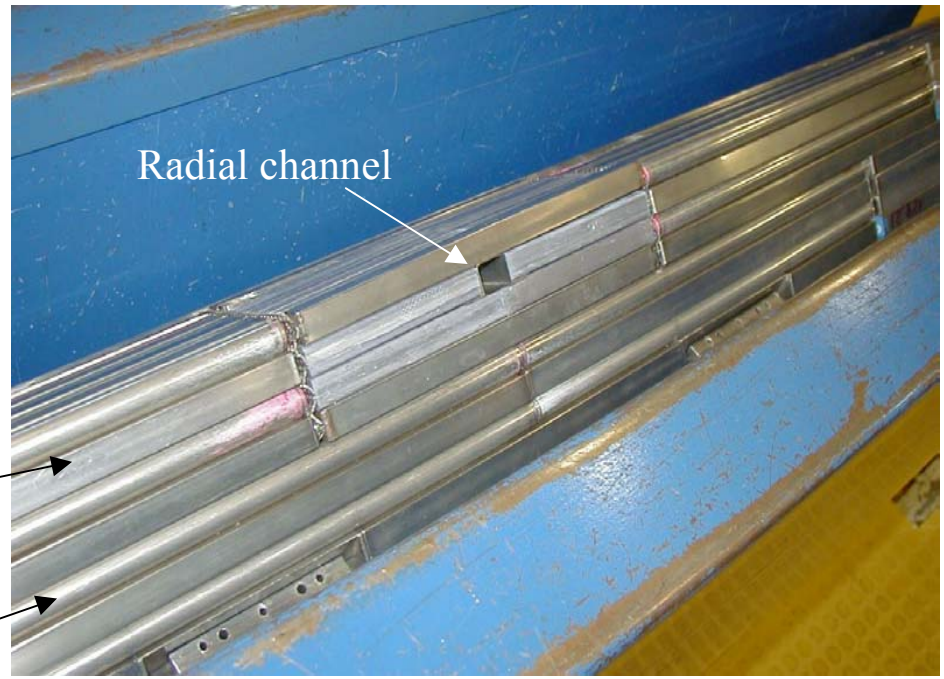
MASURCA core



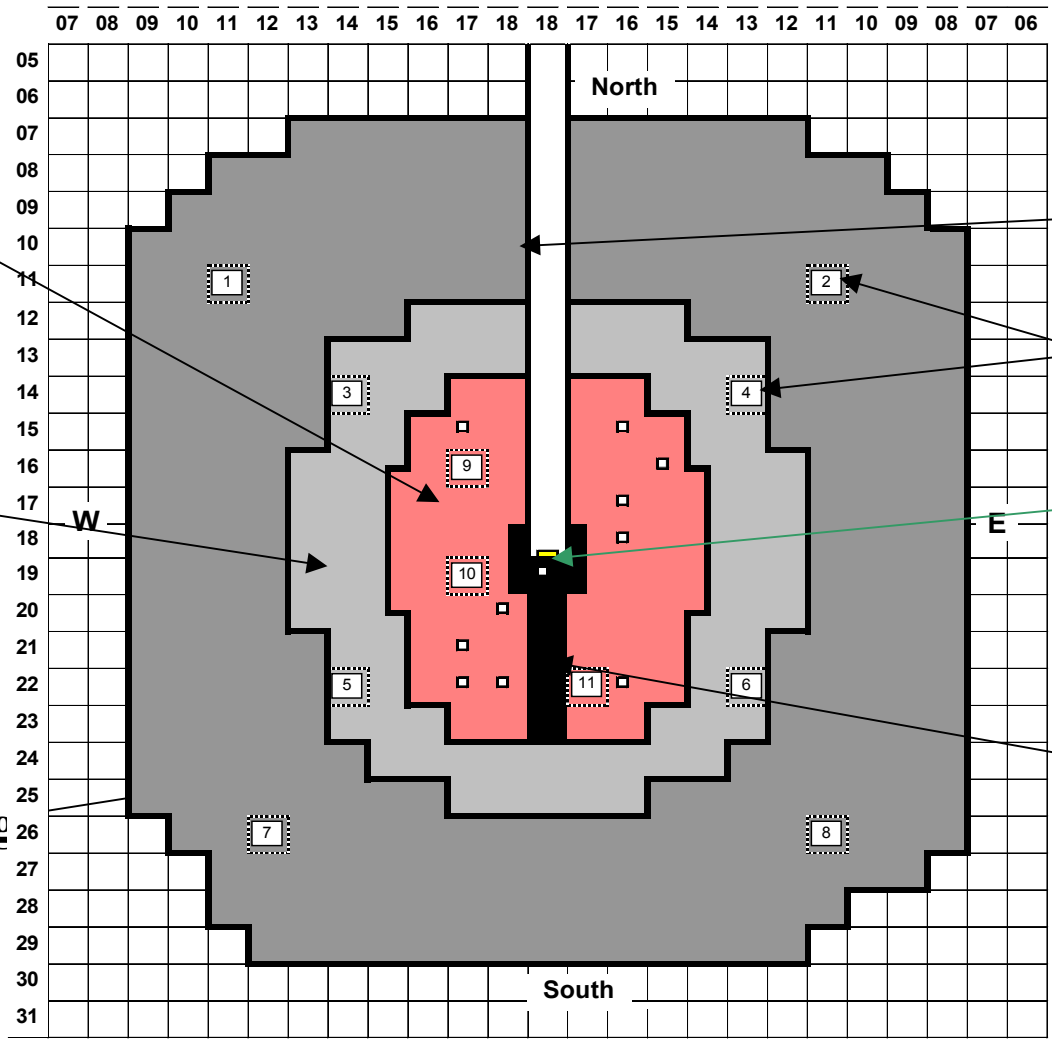
GENEPI tube

MASURCA Fuel





MASURCA Core



Fissile cells

Reflector (Na/SS)

Shielding

GENEPI beam guide

Monitors

Deuterium or Tritium target

Lead zone

GENEPI Accelerator

- Designed and made by CNRS, Grenoble
- D-D reaction (~$1.2.10^8$ n/s at 4 kHz) or D-T (~$1.2.10^{10}$ n/s)
- Pulse duration < 1 μs

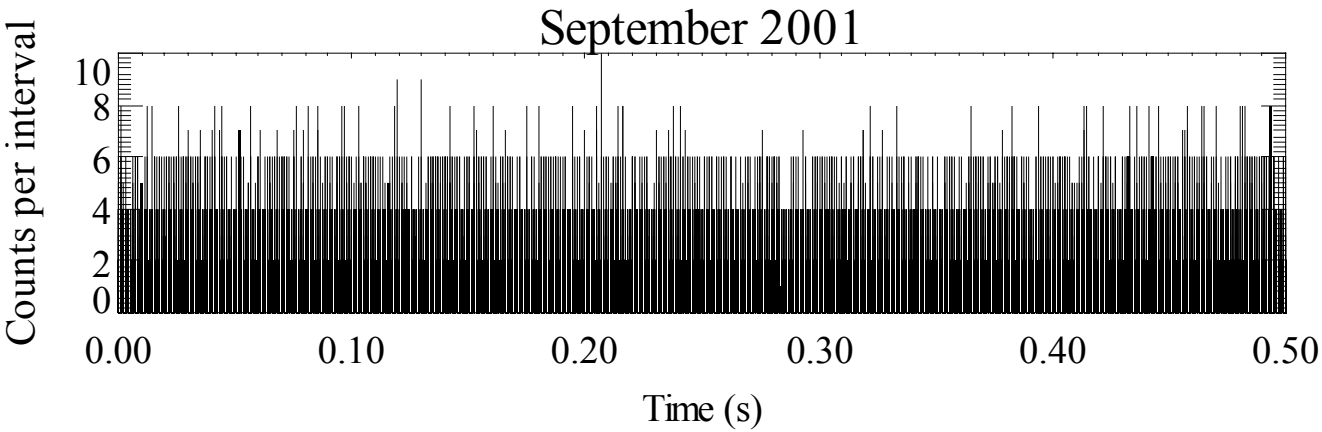
Beam energy (keV)	140 to 240 kev
Peak current (mA)	50
Repetition rate (Hz)	10 to 5 000
Minimum pulse duration (10^{-9} s)	700
Mean beam current (μA)	200 (for a duty cycle of 5 000 Hz)
Pulses reproducibility	Fluctuations at 1% level

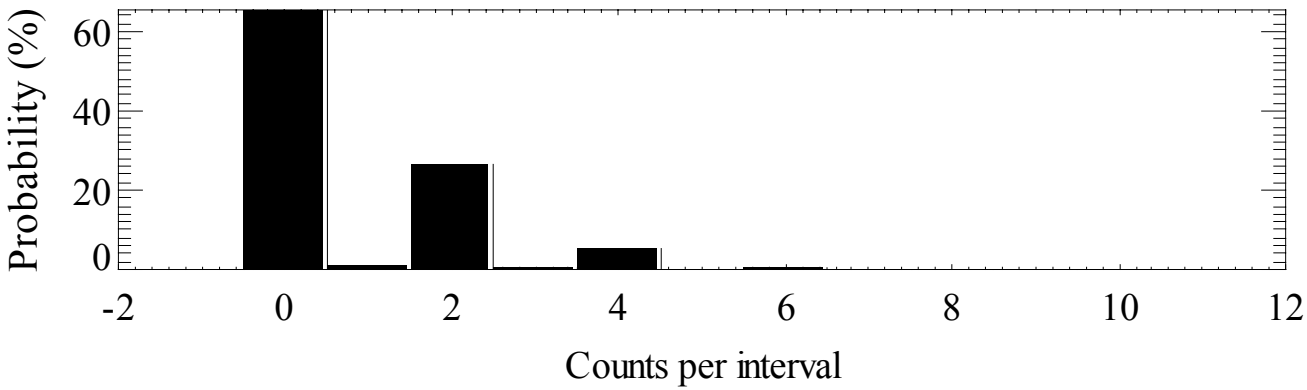
Measurements done by TU-Delft

- Pulse counting measurements (Feynman-α, correlation)
- Continuous current measurements (Transfer function)
- Rod drop measurements (PHYSOR-2002)

Feynman-α results critical

Counts and echoes!





Feynman-α results critical

Pattern	0000	0100	0010	0200	0020	0110
Number	3795830	418	435	1543291	1543460	36306

From the fraction 0110 counts, the delay between each neutron detection and its echo can be extracted: d=115 ns

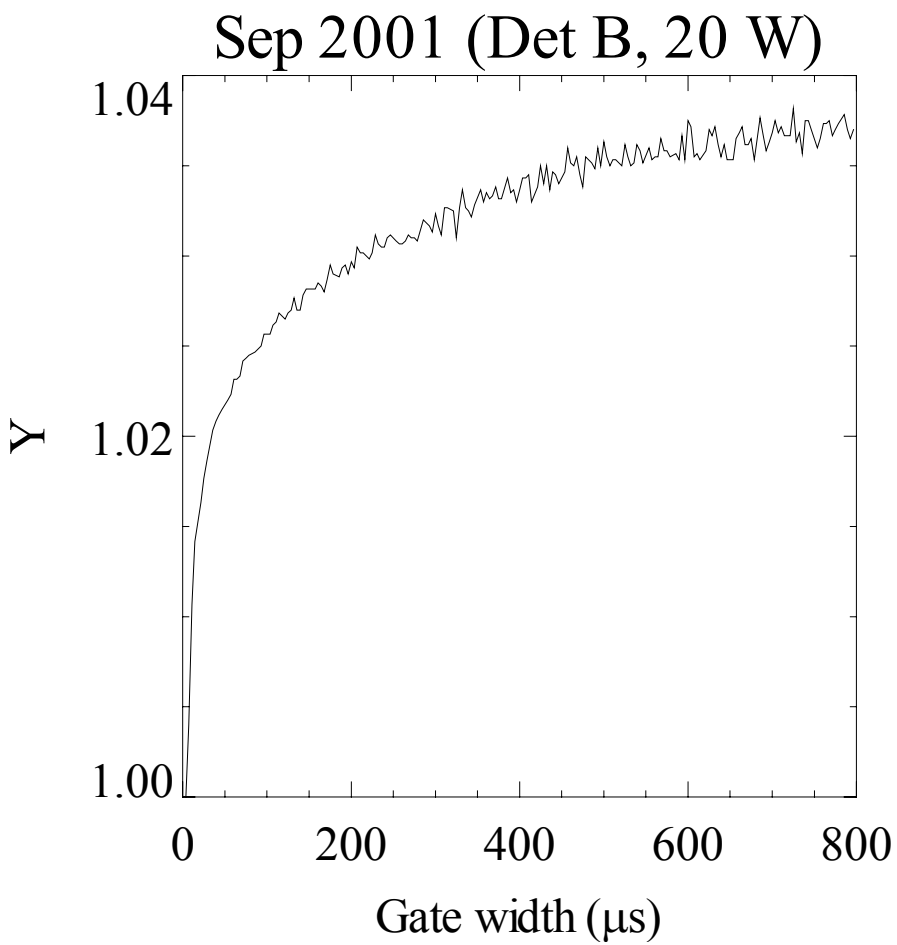
$$Y' = \frac{\sigma^2}{\mu} - 2 + \frac{d}{T} = Y - 1 + \frac{d}{T}.$$

Y = correlated part in variance-to-mean

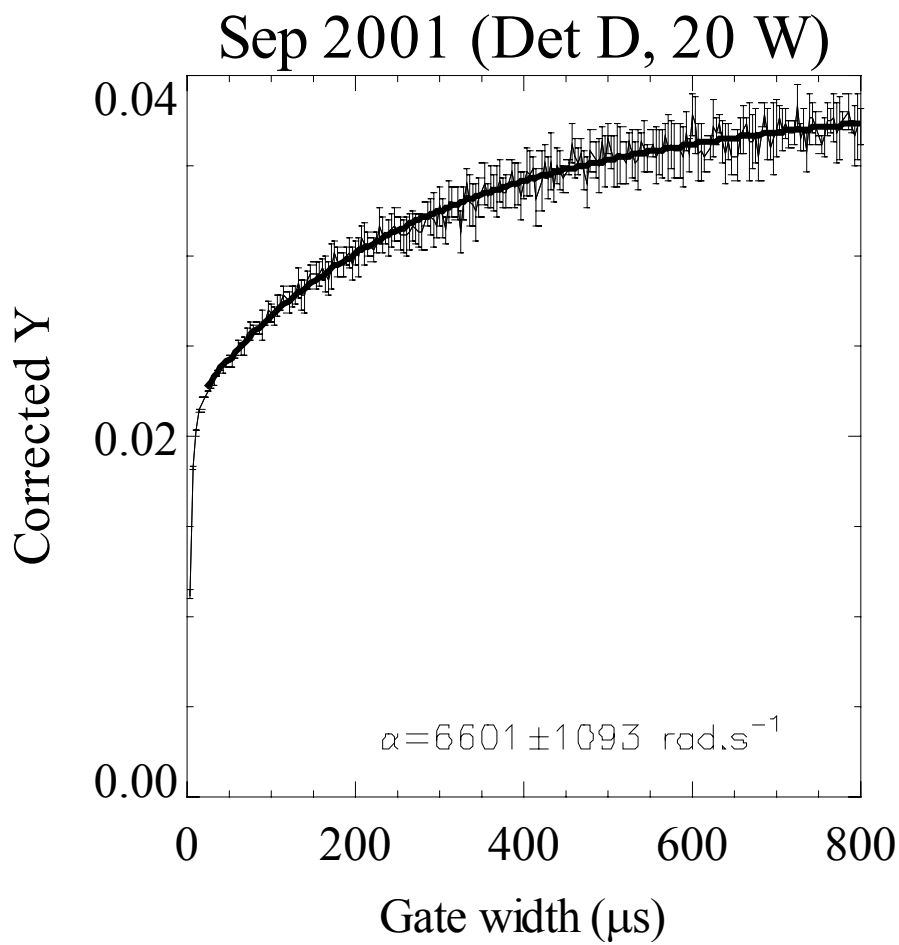
Y' = corrected correlated part in var-to-mean

Feynman-α results critical

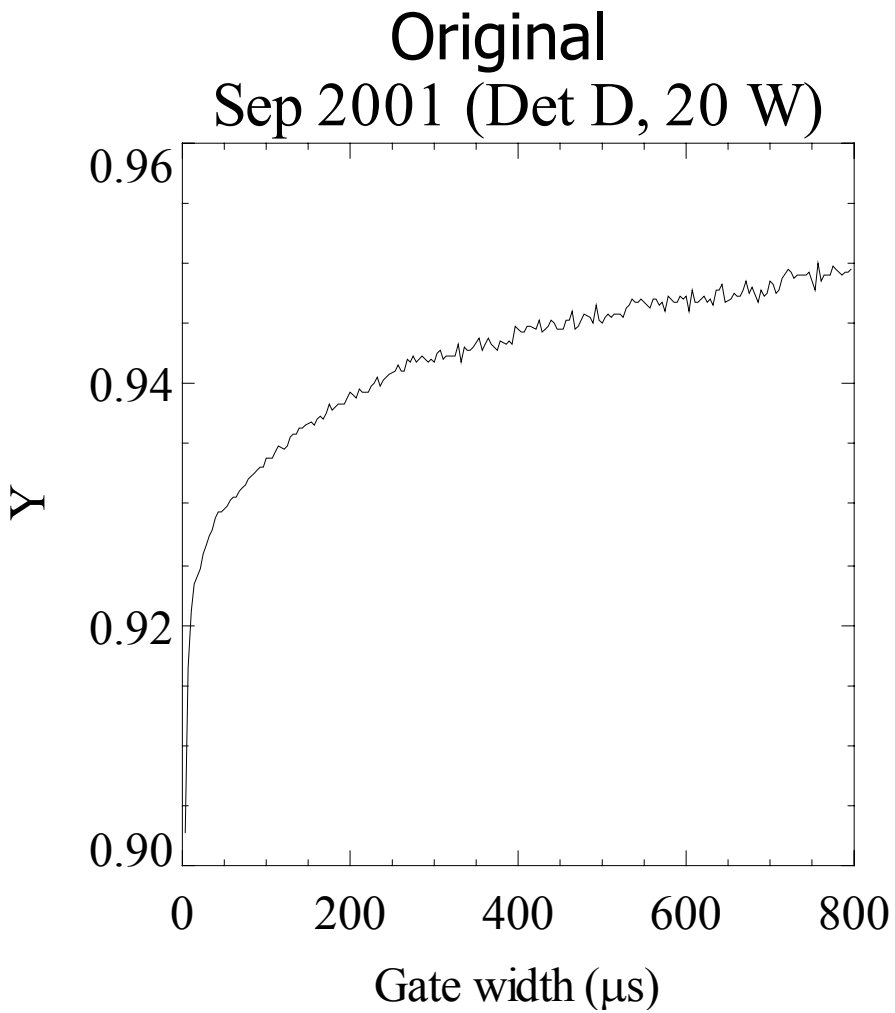
Original

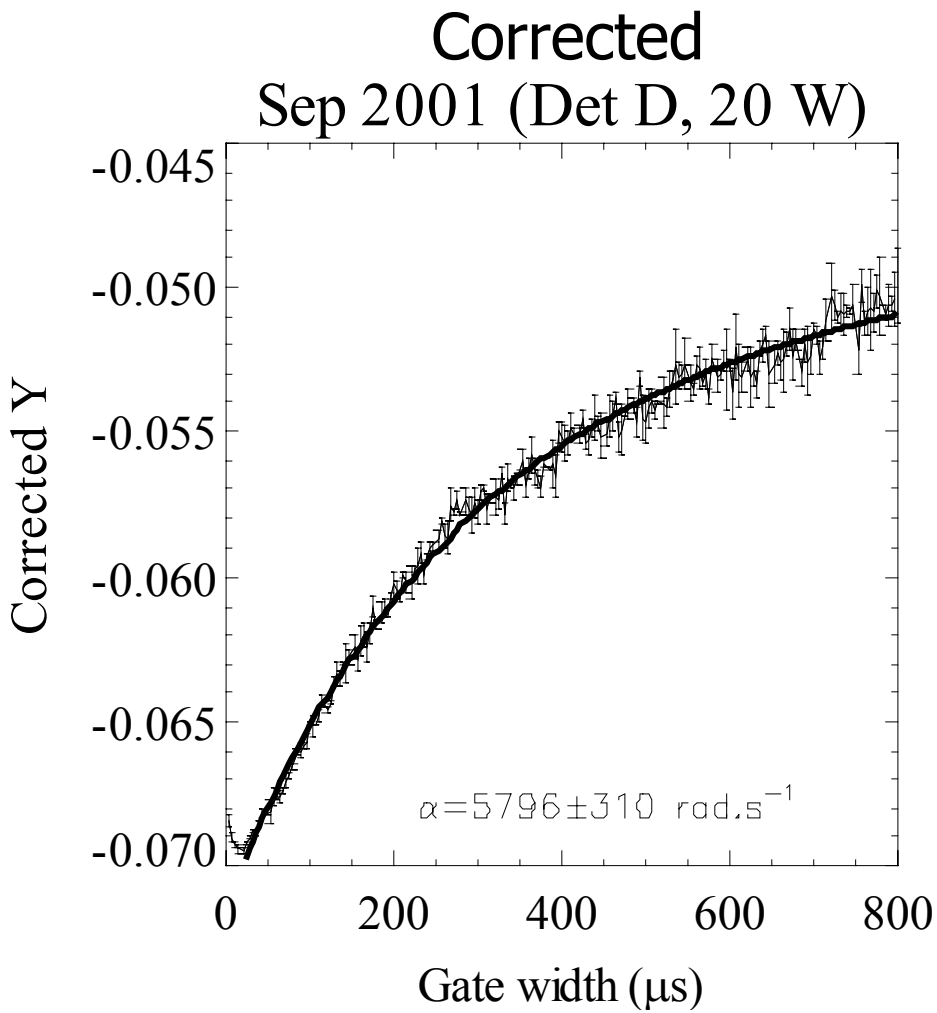


Corrected



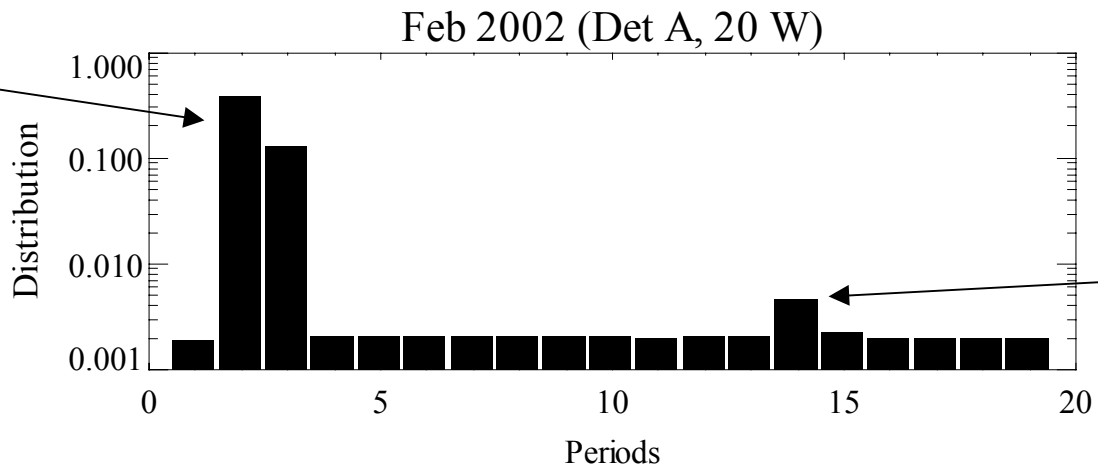
Feynman-α results critical



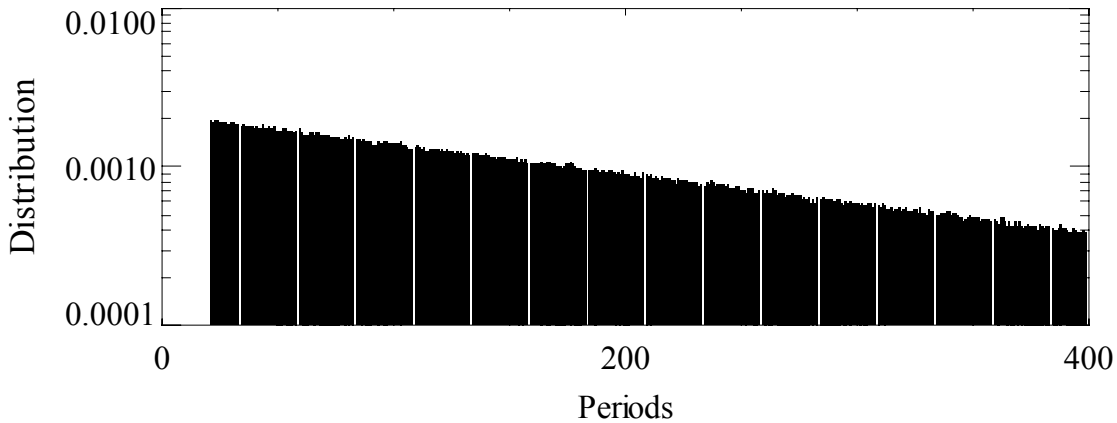


Feynman-α results critical

Echoes at ≈115 ns

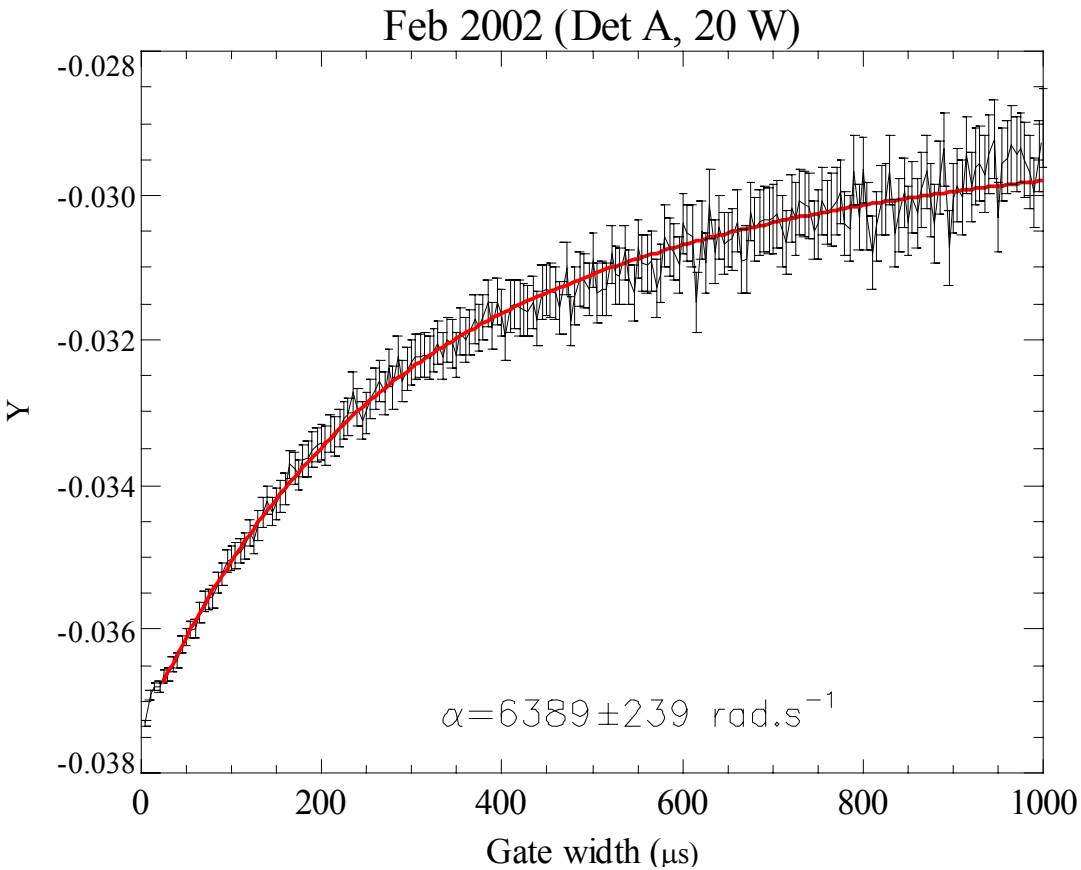


Rebounds ≈720 ns ≈220 m

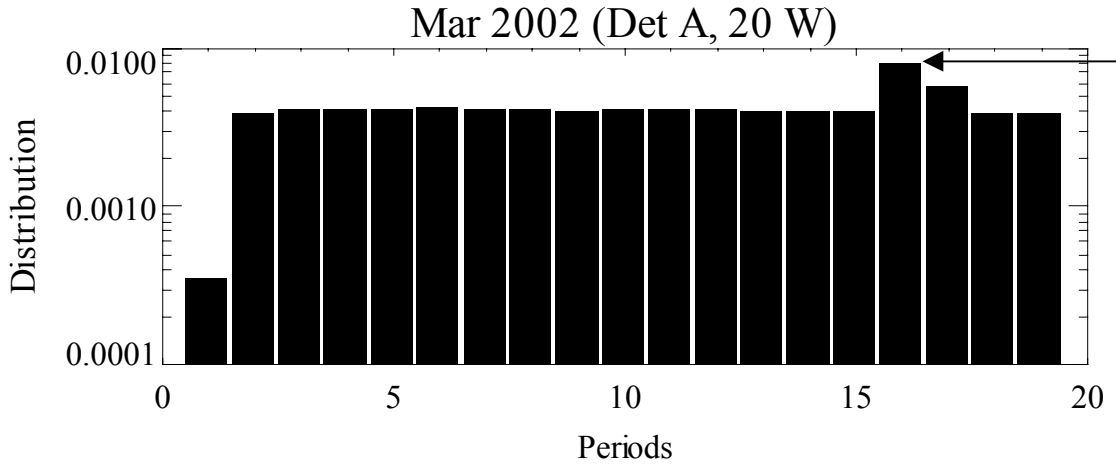


Feynman-α results critical

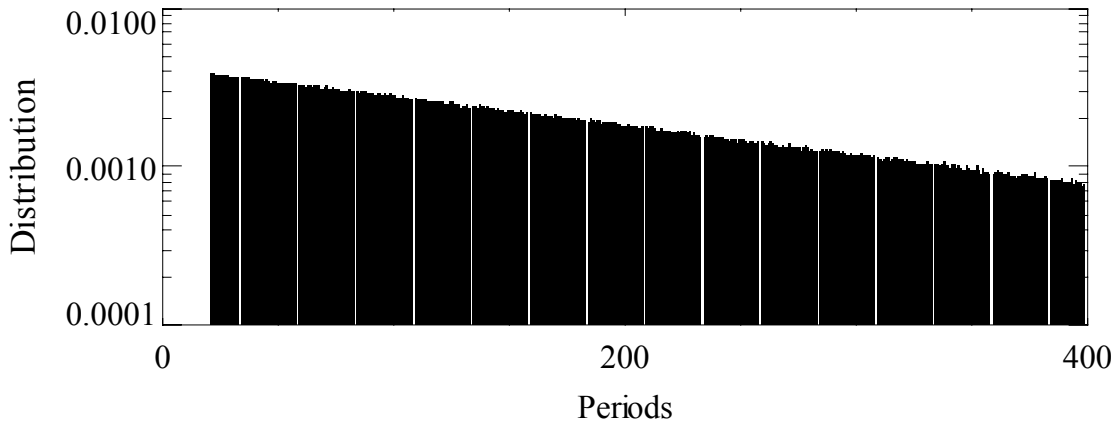
Other measurement method: counts between pulses
All echoes removed within 200 ns after each detection



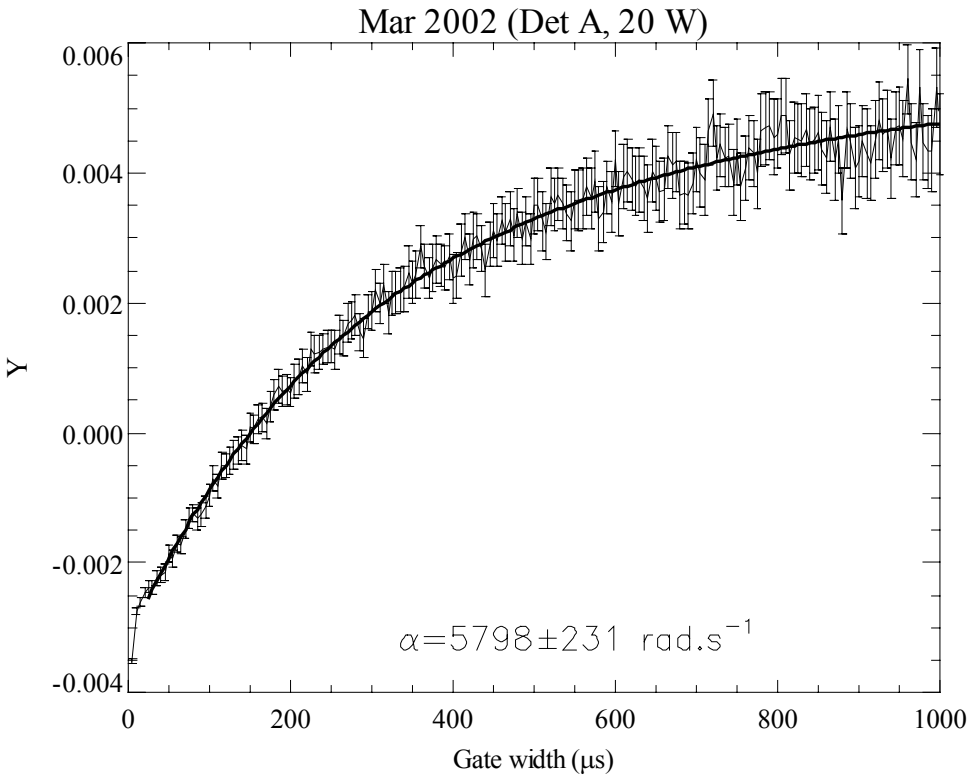
Feynman-α results critical

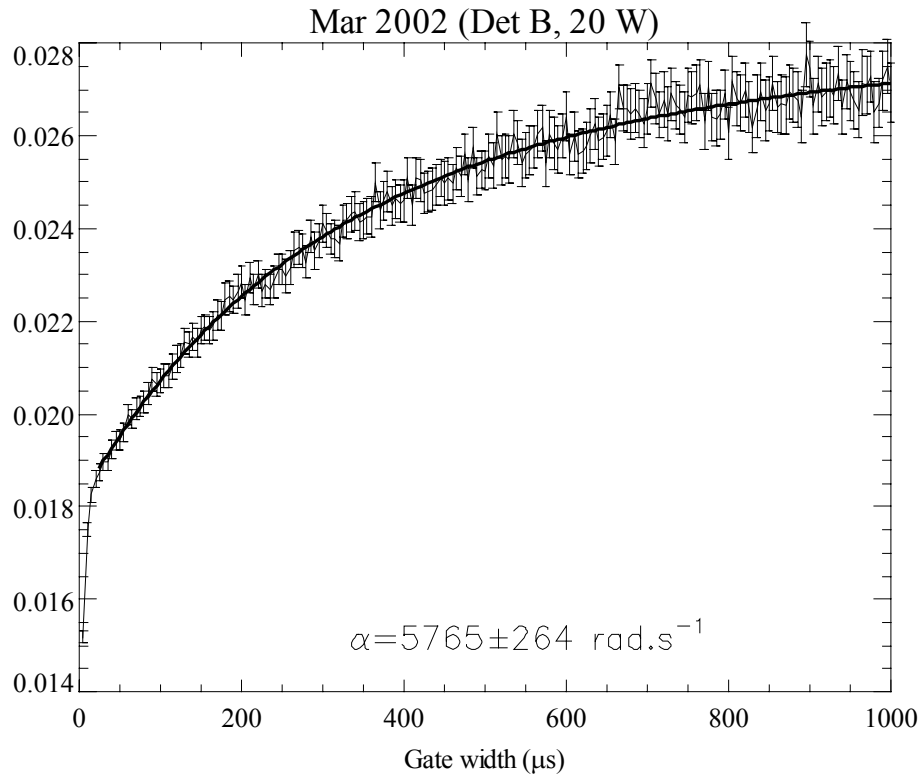


Rebounds
≈800 ns
≈240 m



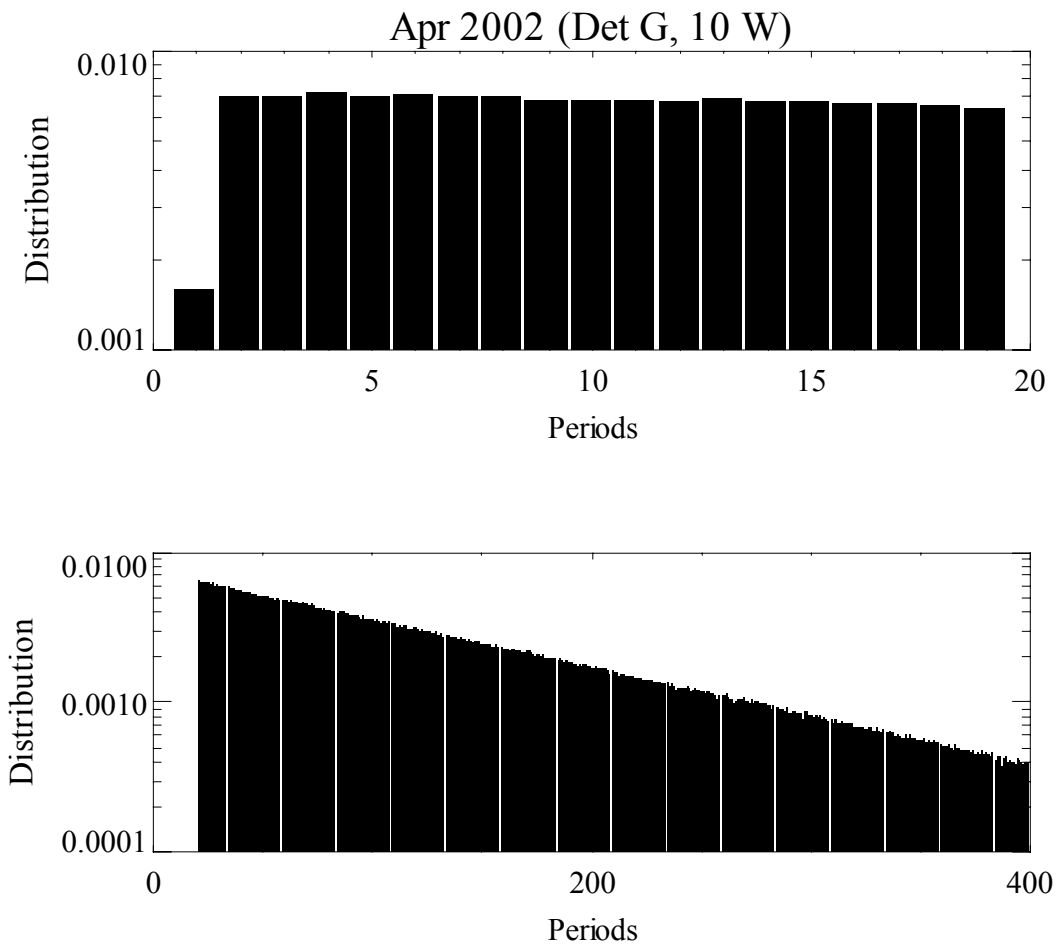
Feynman-α results critical





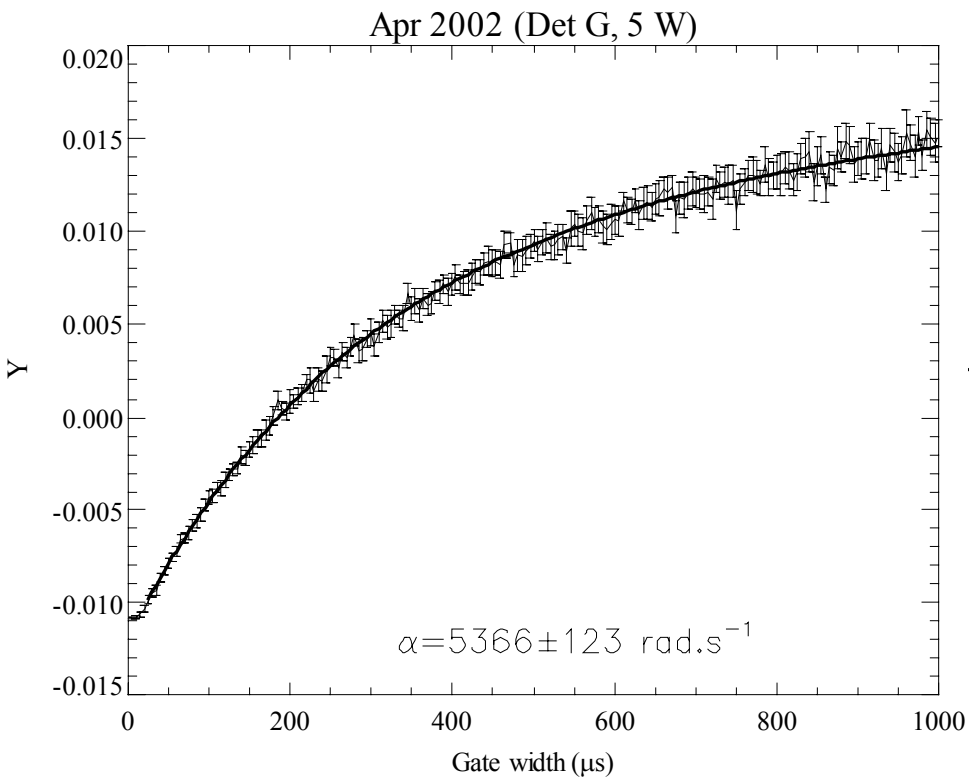
Calculations: β=335 pcm, Λ=0.586 μs, α≈5720 s^{-1}

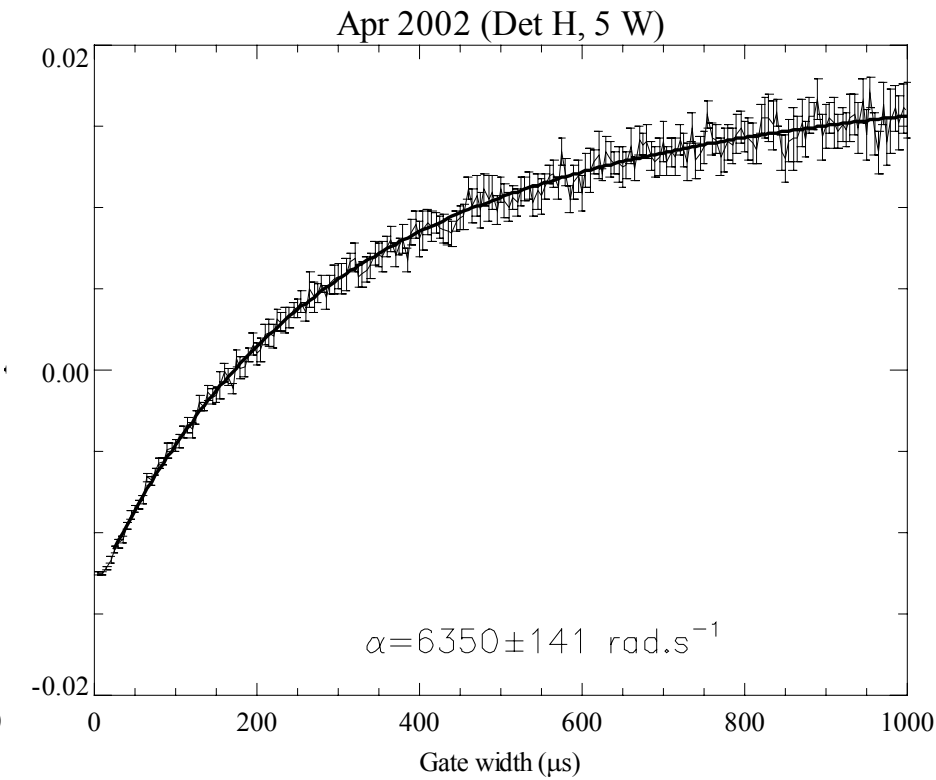
Feynman-α results critical



Feynman-α results critical

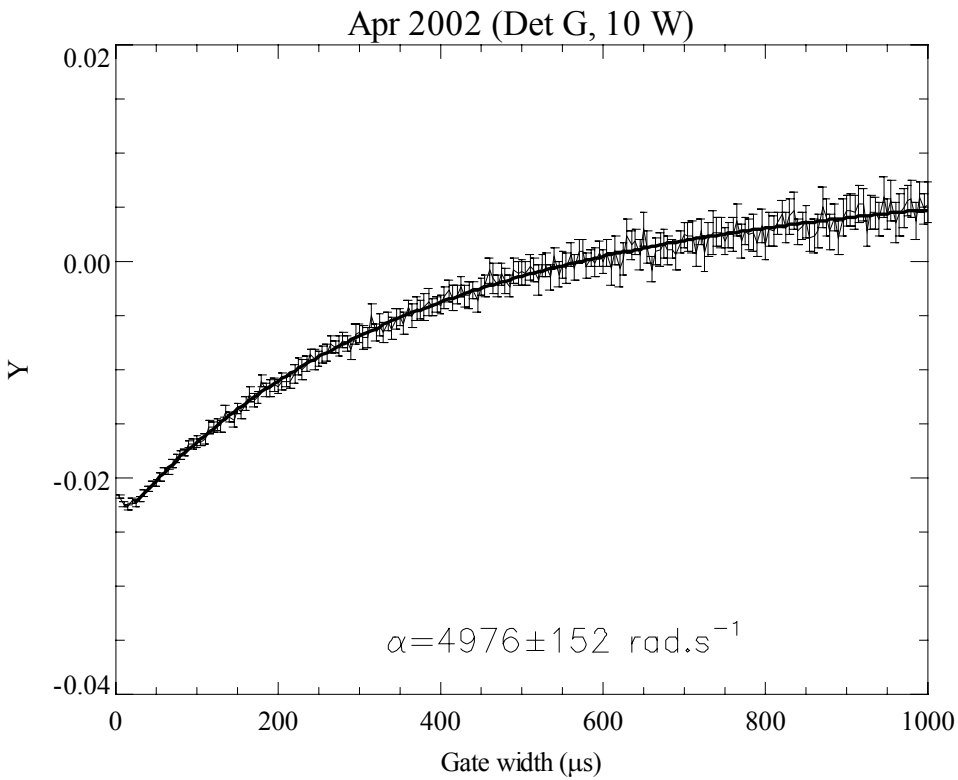
Reactor power 5 W

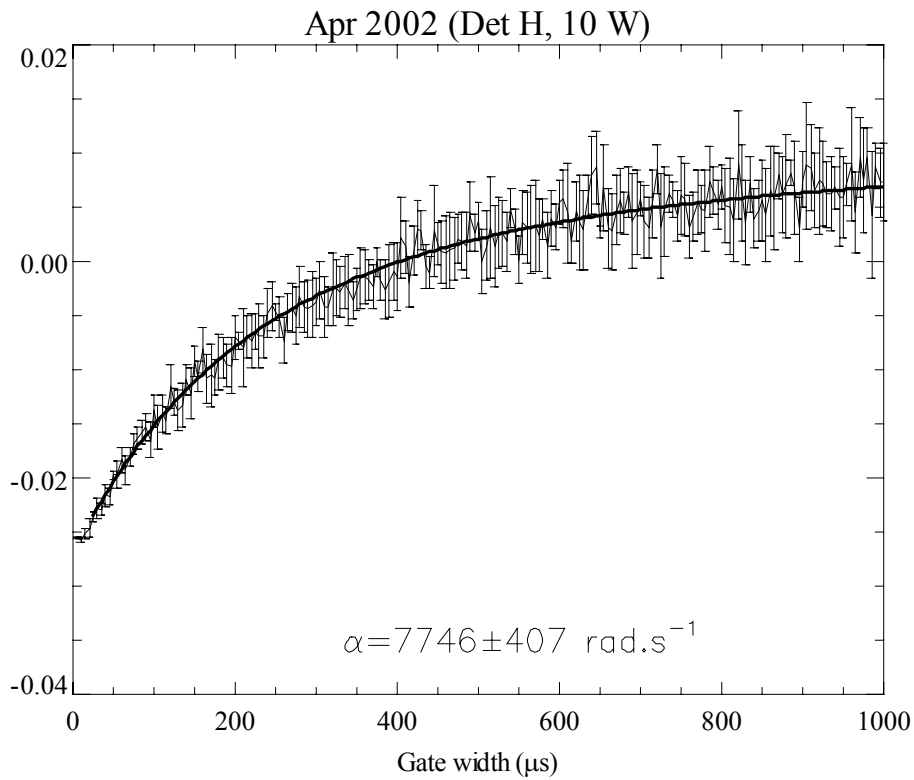




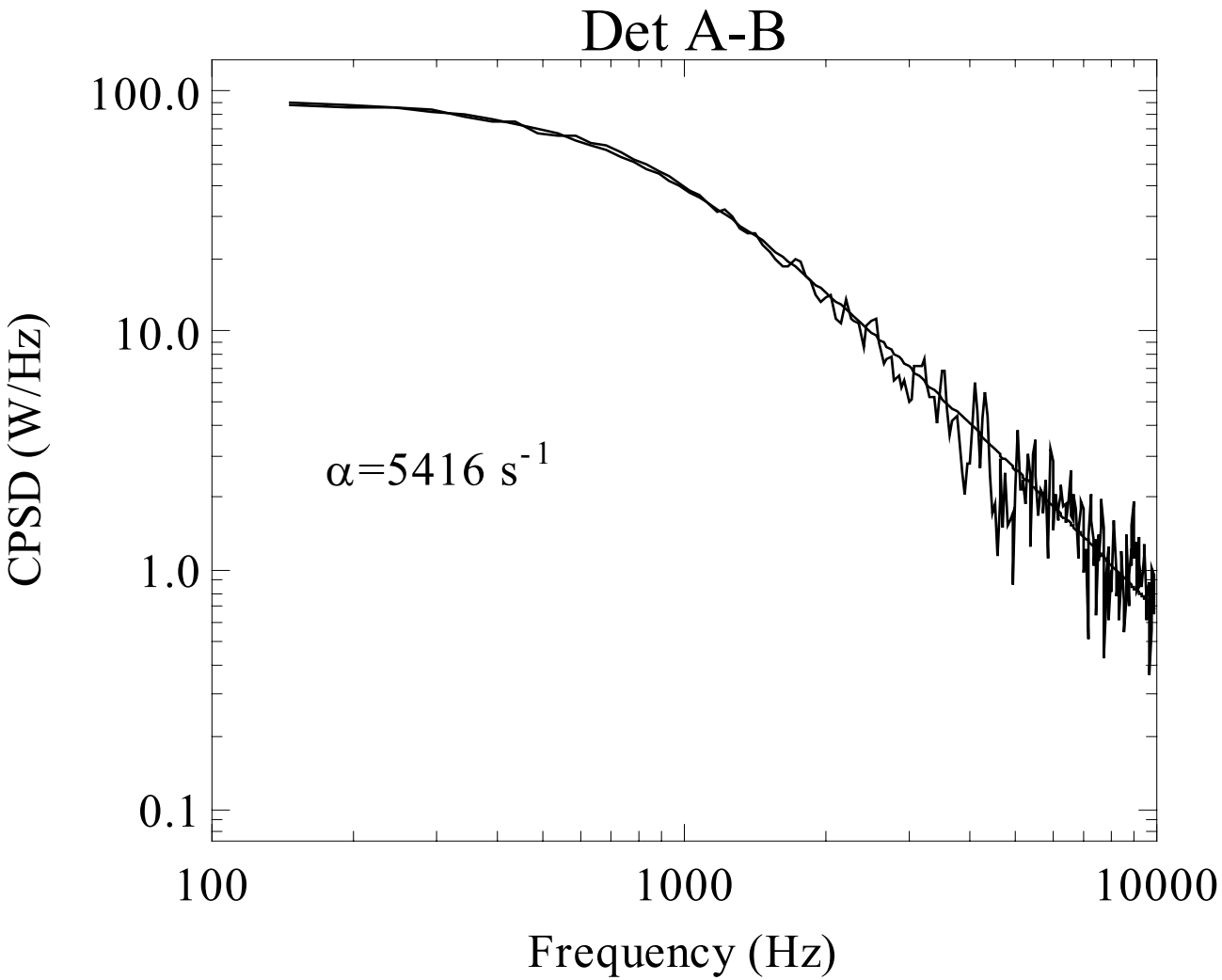
Feynman-α results critical

Reactor power 10 W





CPSD results critical



Calculations:

- β=335 pcm
- Λ=0.586 μs
- α≈5720 s^{-1}

Feynman-α pulsed subcritical systems

Pazsit et al (PHYSOR 2002),

Yamana et al (PHYSOR 2002),

Kitamura et al (ANE, **38**, 879-909):

Stochastically pulsed system:

$$Y(T) = \frac{\sigma^2(T)}{\mu(T)} - 1 = \frac{2\varepsilon S_0 T_p^5 \alpha}{T\pi^4} \sum_{n=0}^{\infty} \frac{1}{4n^6\pi^2 + n^4\alpha^2 T_p^2} \sin^2\left(\frac{\pi n\tau}{T_p}\right) + \frac{\varepsilon\lambda_f \overline{\nu(\nu-1)}}{\alpha^2}\left(1 - \frac{1-\mathrm{e}^{-\alpha T}}{\alpha T}\right)$$

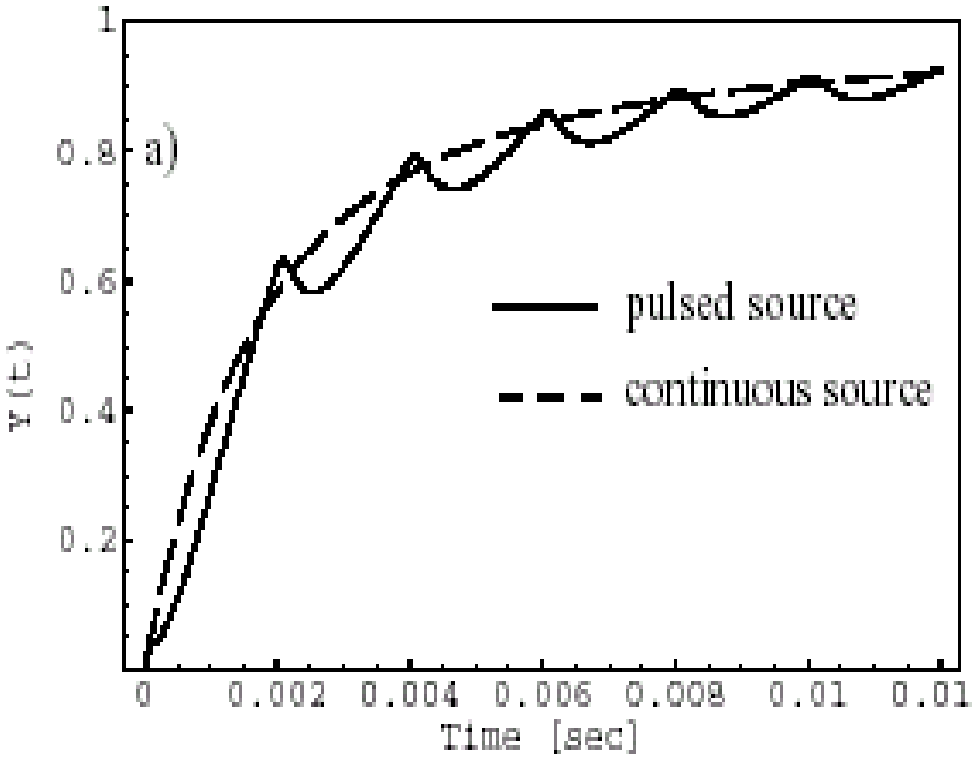
Deterministically pulsed system:

$$Y(T) = \frac{\lambda_d \lambda_f \langle \nu(\nu-1)\rangle}{\alpha^2} \frac{\left\{ \begin{array}{l} 2\Delta_{\alpha\tau}\left(1 - \mathrm{e}^{-\alpha T} - \alpha T \mathrm{e}^{-\alpha T}\right) + \Delta_{2\alpha\tau}(\delta - 1)\left(1 - \mathrm{e}^{-\alpha T}\right)^2 \\ + \sum_{m=1}^{M} \left[\begin{array}{l} 2\left\{1 - \mathrm{e}^{-\alpha(T-m\tau)} - \alpha(T-m\tau)\mathrm{e}^{-\alpha(T-m\tau)}\right\} \\ +(\delta = 1)\left\{1 - \mathrm{e}^{-\alpha(T-m\tau)}\right\}^2 \end{array} \right] \end{array} \right\}}{\Delta_{\alpha\tau}\left(1 - \mathrm{e}^{-\alpha T}\right) + \sum_{m=1}^{M} \left\{1 - \mathrm{e}^{-\alpha(T-m\tau)}\right\}}$$

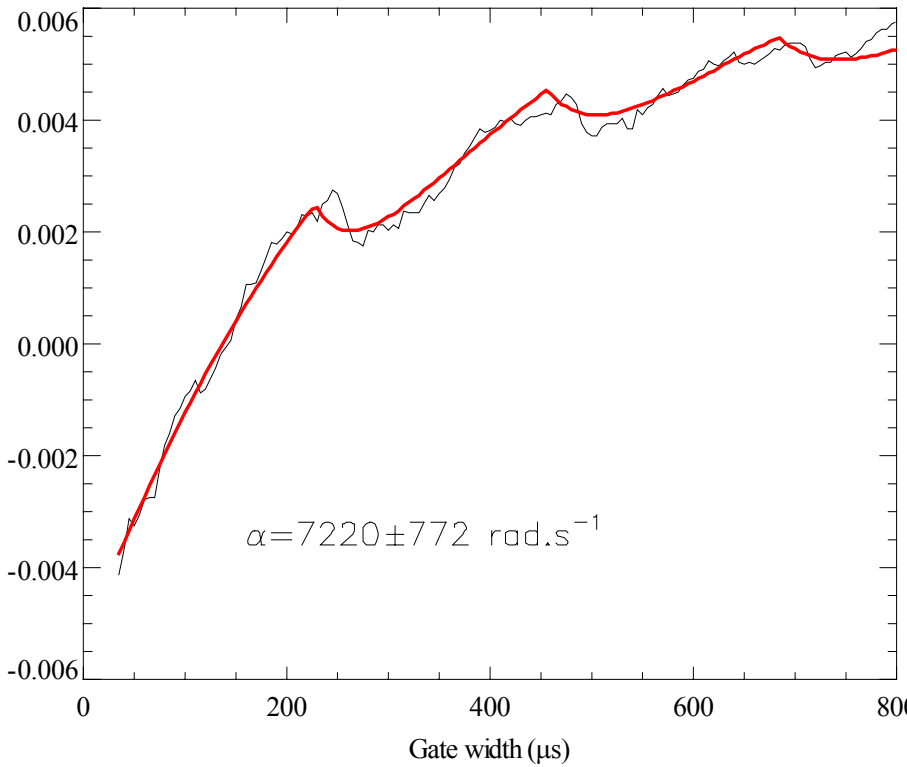
Feynman-α results subcritical

Deterministically pulsed system; D-D @ 4.4 kHz

Theory (I. Pazsit)



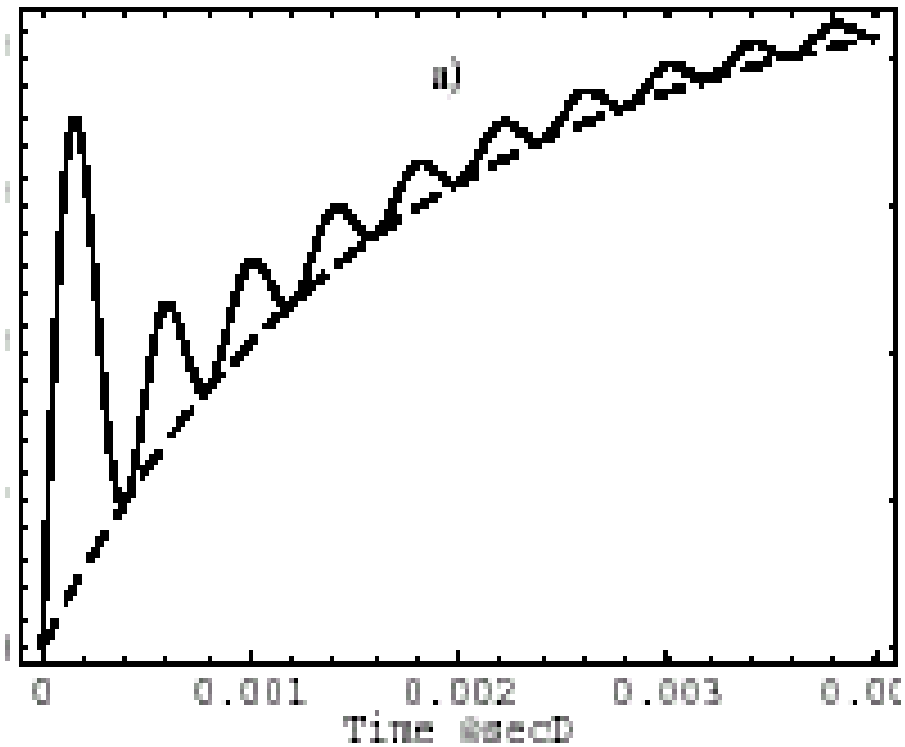
Experiment (D-D)



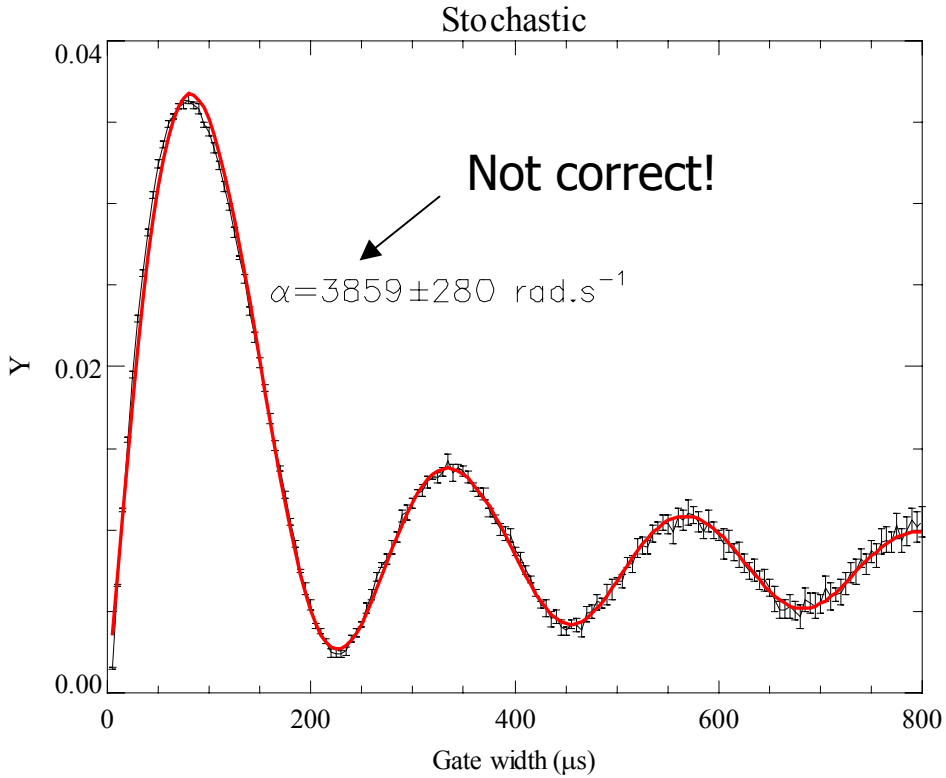
Feynman-α results subcritical

Stochastically pulsed system; D-D @ 4.4 kHz

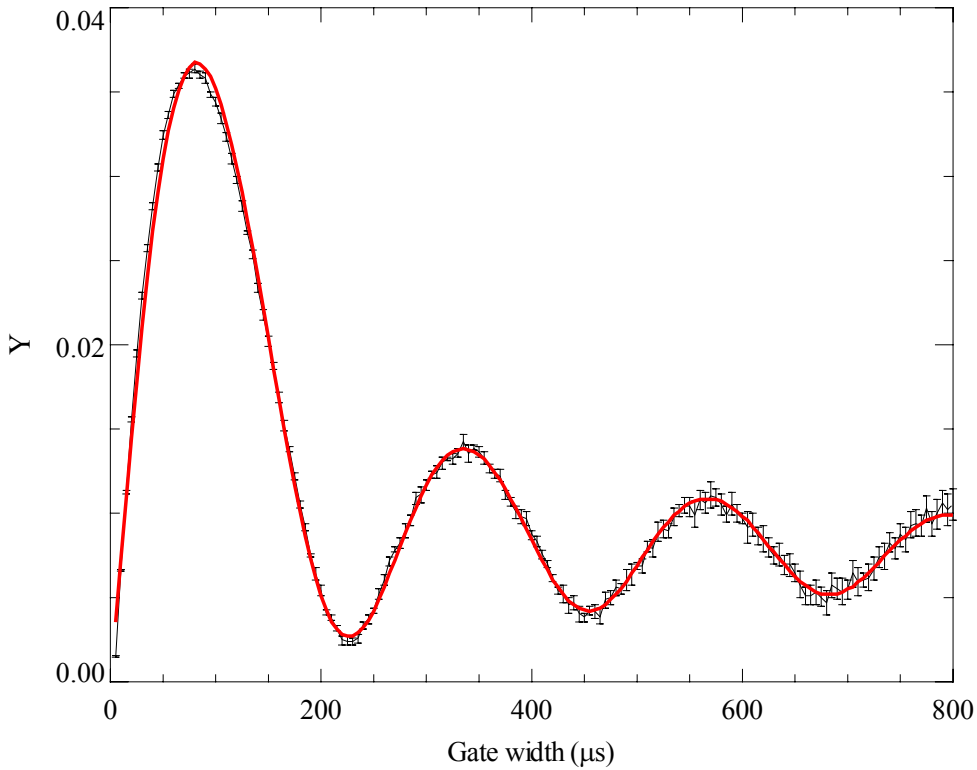
Theory (I. Pazsit)

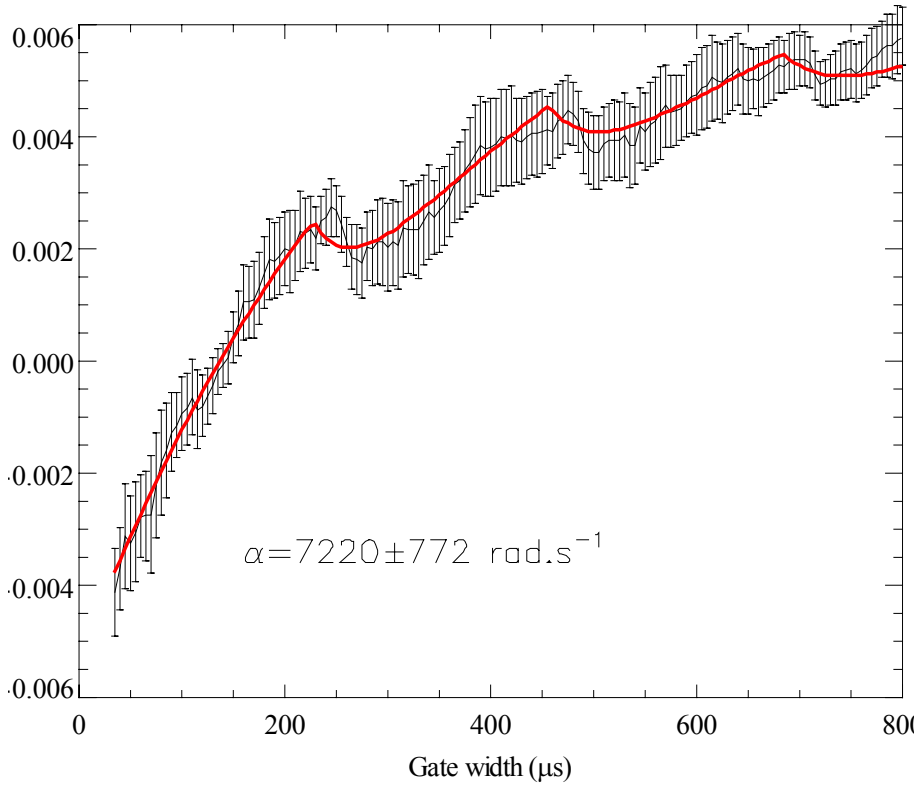


Experiment (D-D)

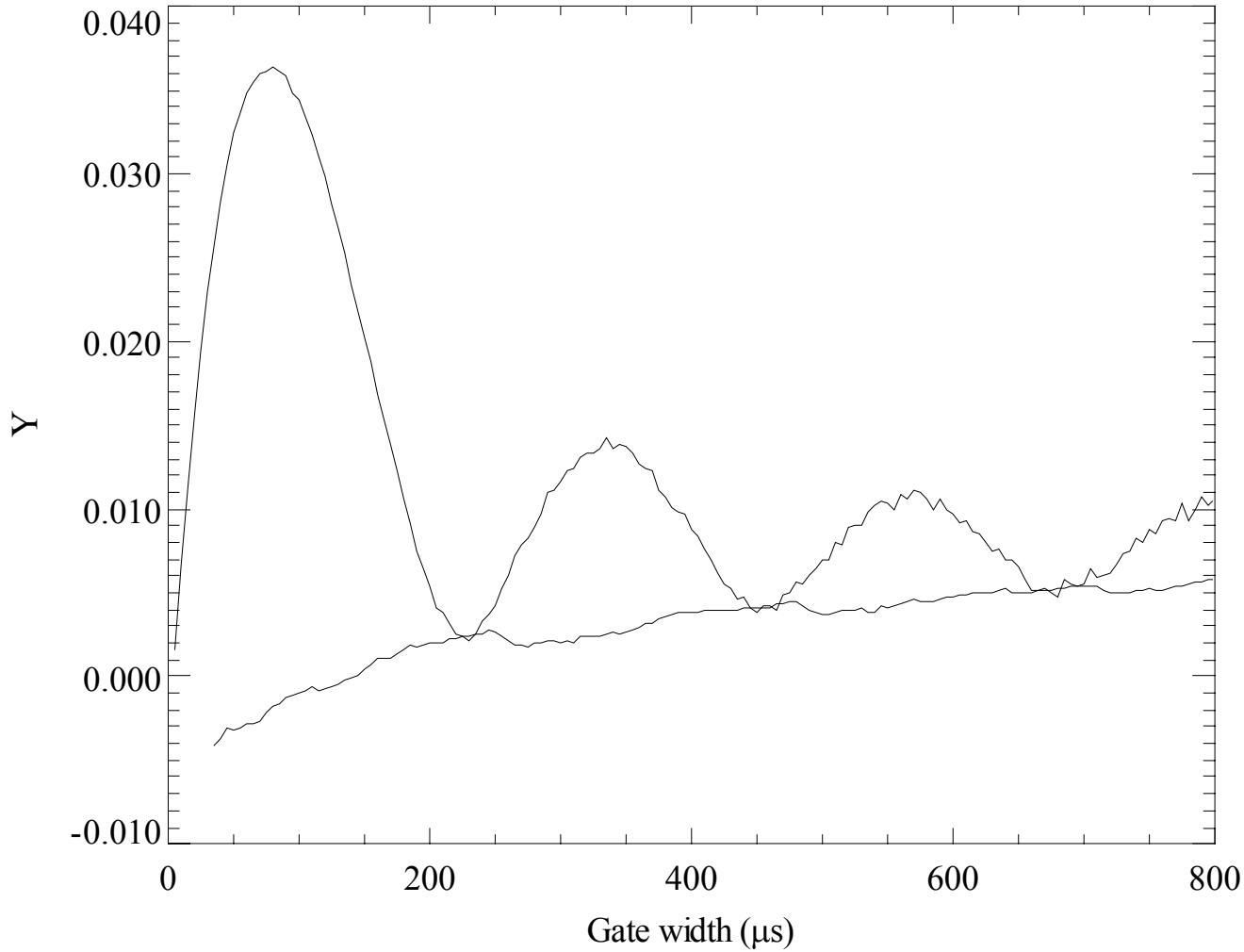


Feynman-α results subcritical

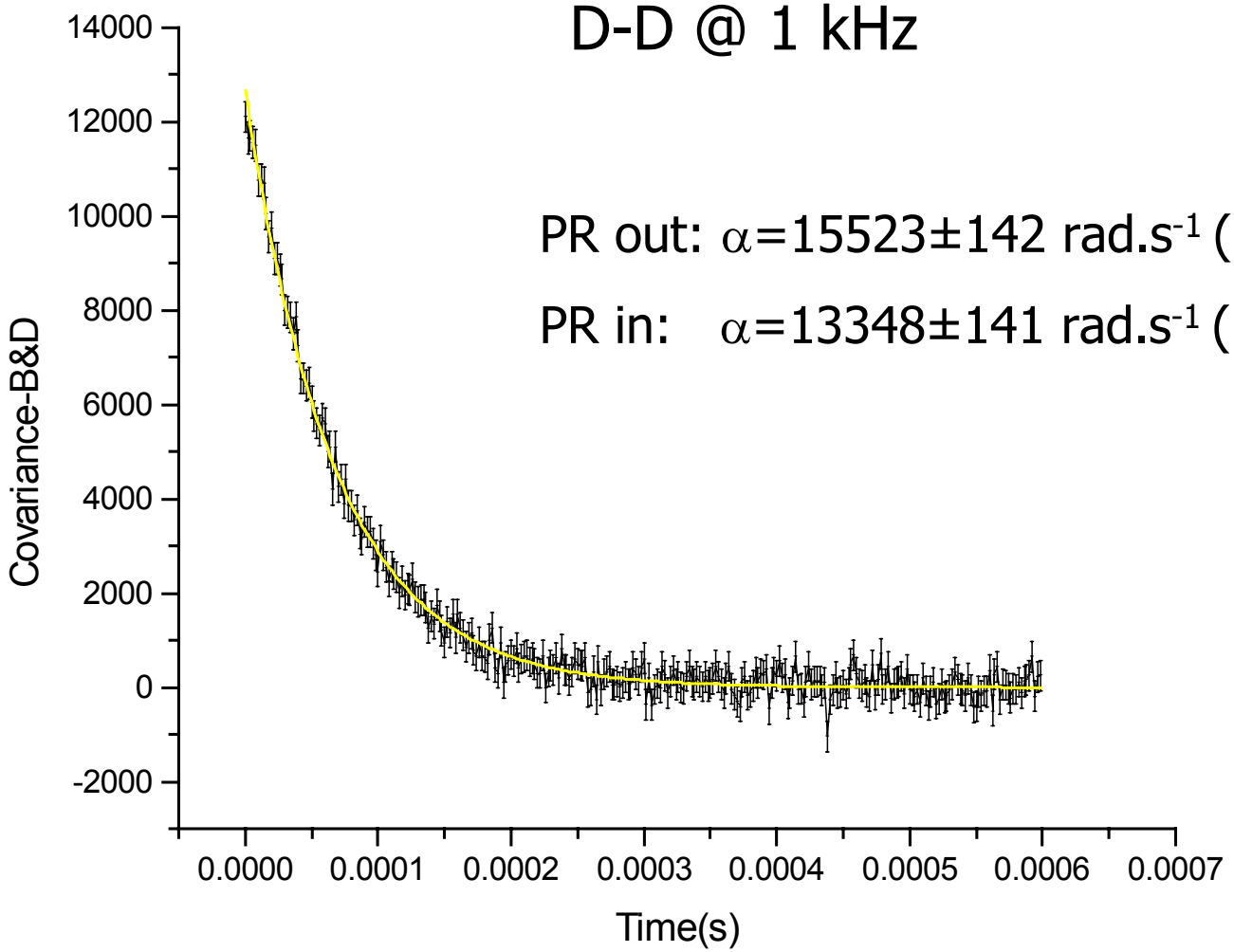




Feynman-α results subcritical



Correlation results ≈1.5$ subcritical

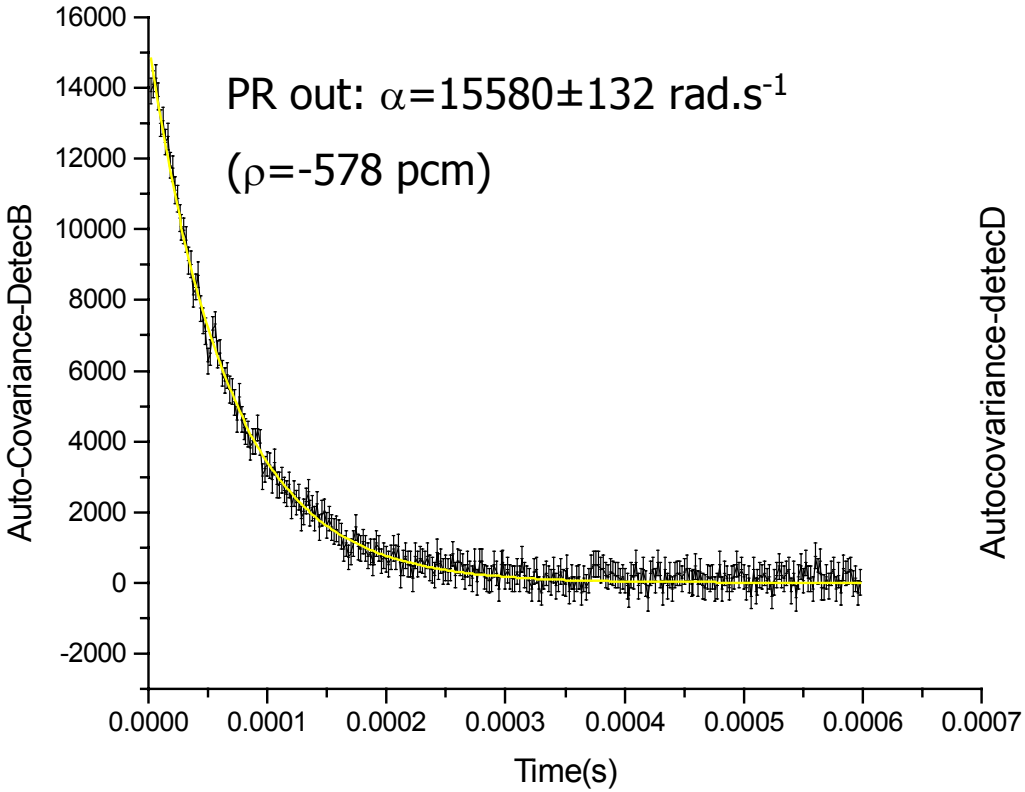


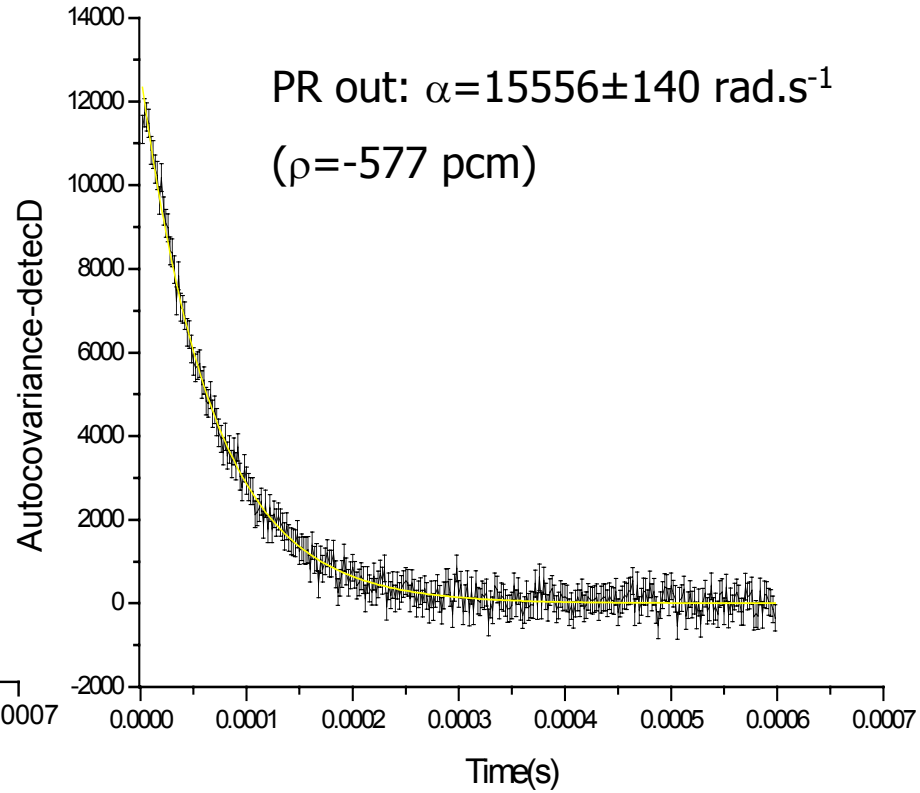
PR out: α=15523±142 rad.s^{-1} (ρ=-575 pcm)

PR in: α=13348±141 rad.s^{-1} (ρ=-447 pcm)

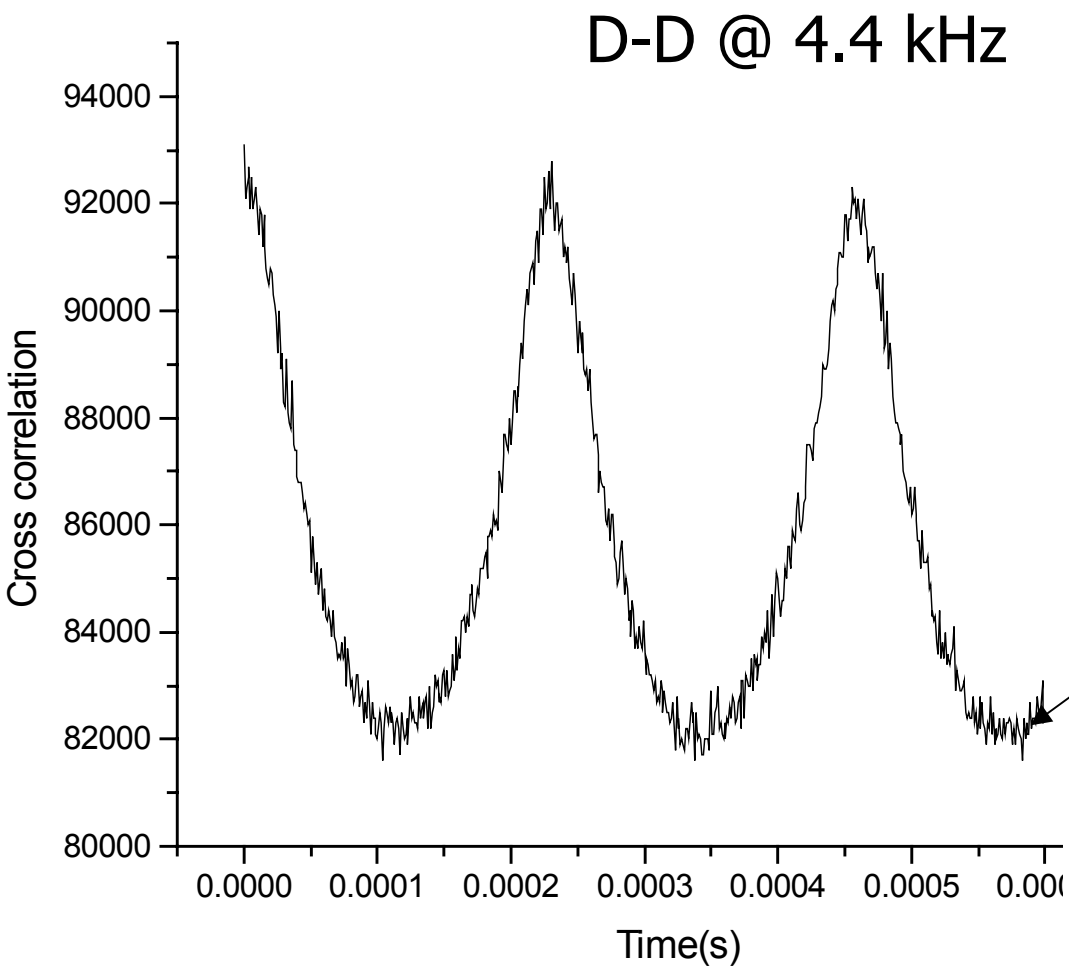
Correlation results ≈1.5$ subcritical

D-D @ 1 kHz





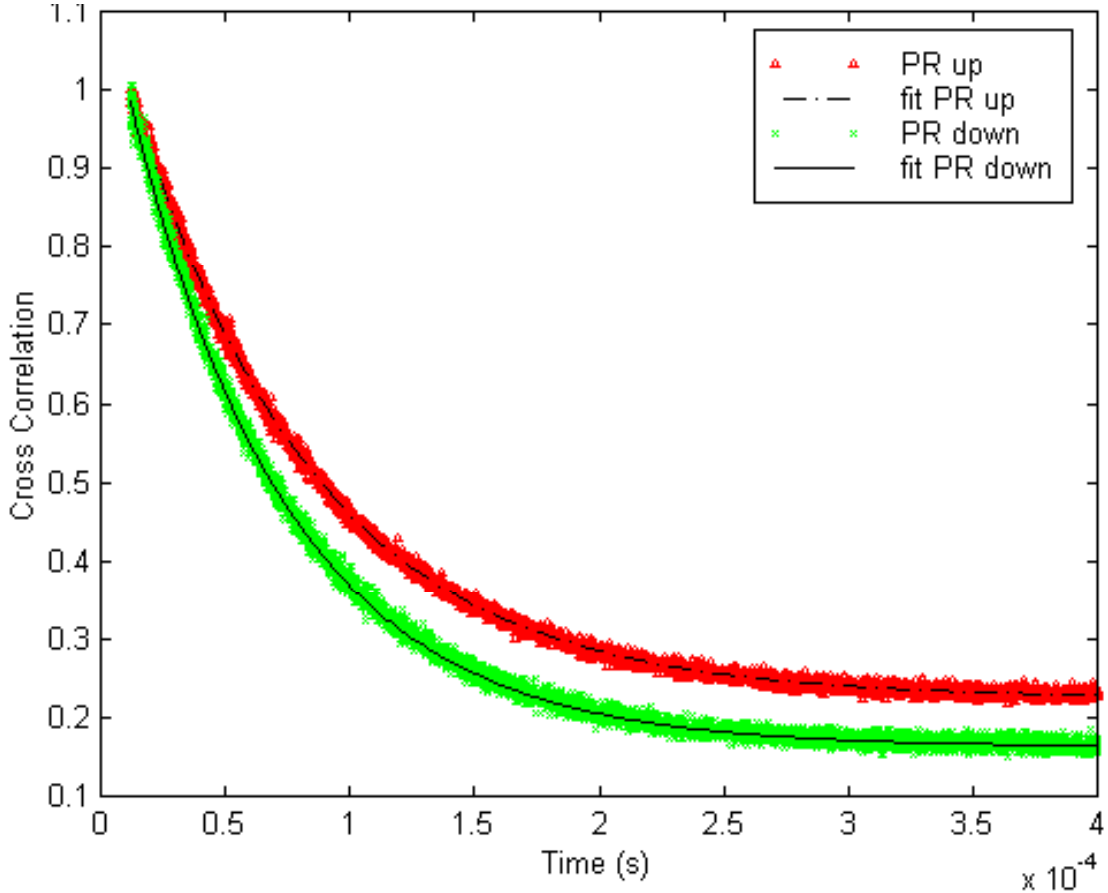
Correlation results ≈1.5$ subcritical



Frequency too high:
Overlap of chains !

Correlation results ≈1.5$ subcritical

D-T @ 1 kHz



Pilot rod out:

α=15752 rad.s^{-1}

(ρ=-588 pcm)

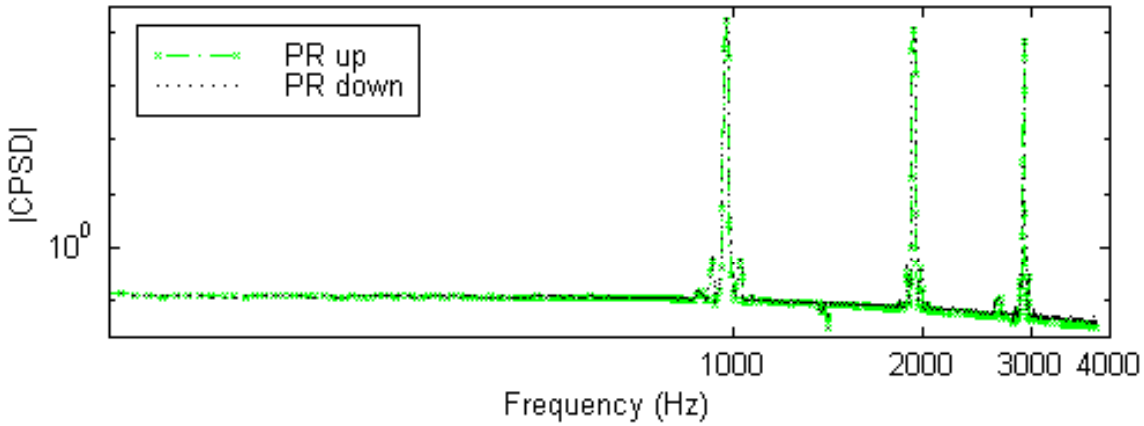
Pilot rod in:

α=13598 rad.s^{-1}

(ρ=-462 pcm)

CPSD results ≈1.5$ subcritical

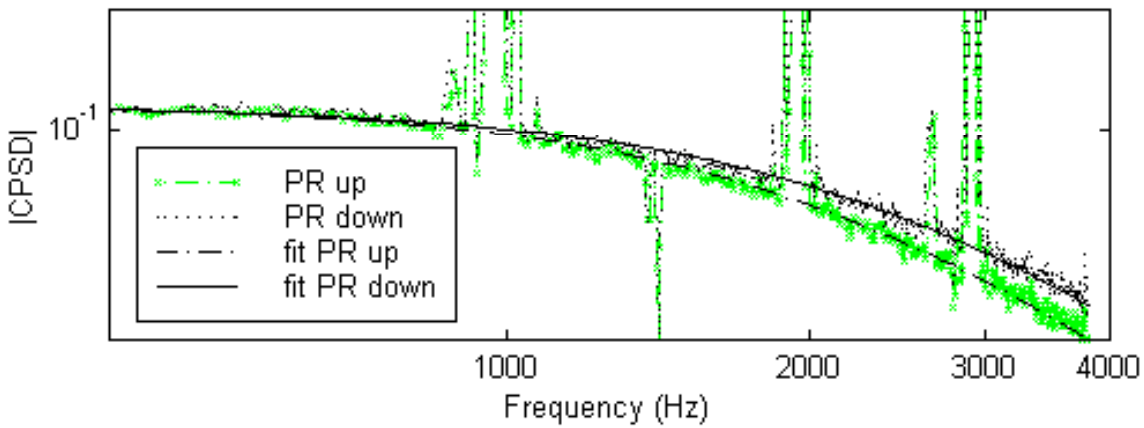
D-T @ 1 kHz



Pilot rod out:

α=16023 rad.s^{-1}

(ρ=-604 pcm)



Pilot rod in:

α=13930 rad.s^{-1}

(ρ=-481 pcm)

Conclusions and further work

- Modification to Feynman-α to correct for echoes successful
- Feynman-α values in agreement with correlation and others
- Experimental Feynman-α results for pulsed systems
- Cross-correlation and CPSD give very fast accurate results
- Needed to remove peaks from the CPSD before fitting
- Comparison with other experimental groups under way
- Analysis of measurements at other configurations (SC2)