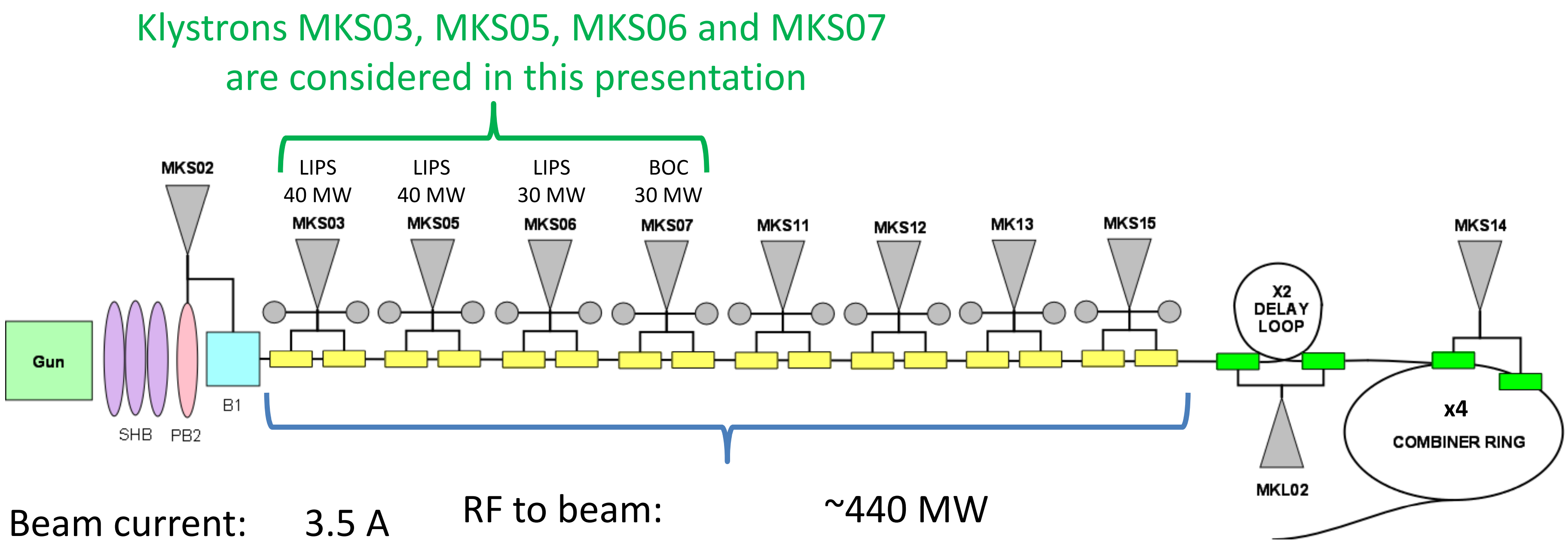
RF phase & *amplitude* stability of the CTF klystrons

By Dubrovskiy Alexey

And thanks to Frank Tecker and Daniel Schulte

Layout of klystrons in the CTF



Beam current: 3.5 A
Beam frequency: 1.5 GHz

RF to beam: ~440 MW
Pulse length: 1.6 µs
Accelerating gradient : 7 MV/m
Klystron frequency: 3 GHz

From G. McMonagle, CLIC-Note- 694

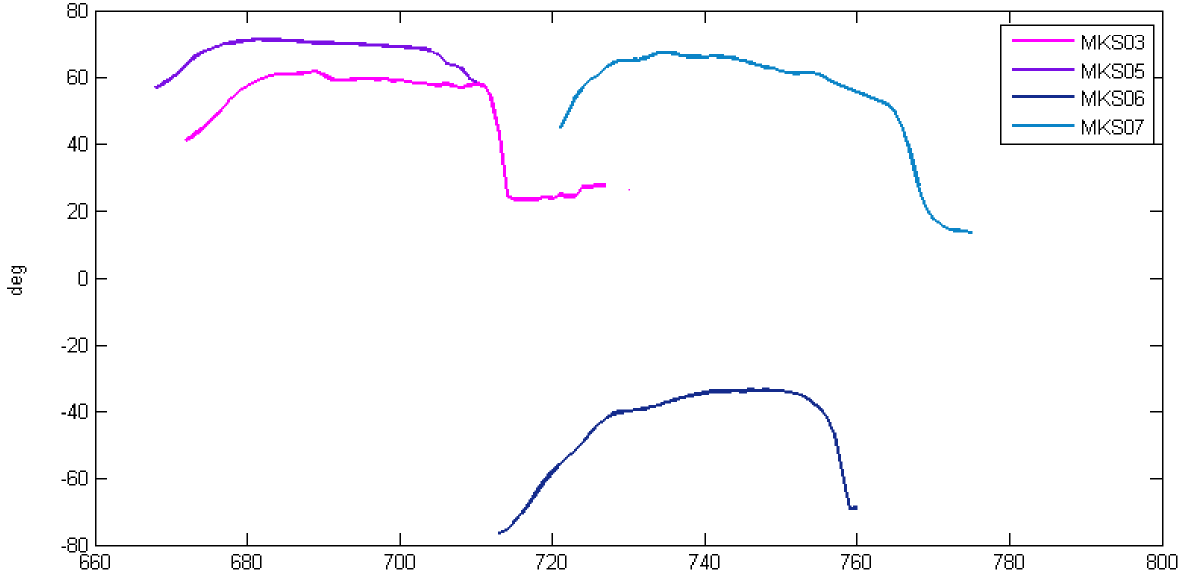
Single pulse

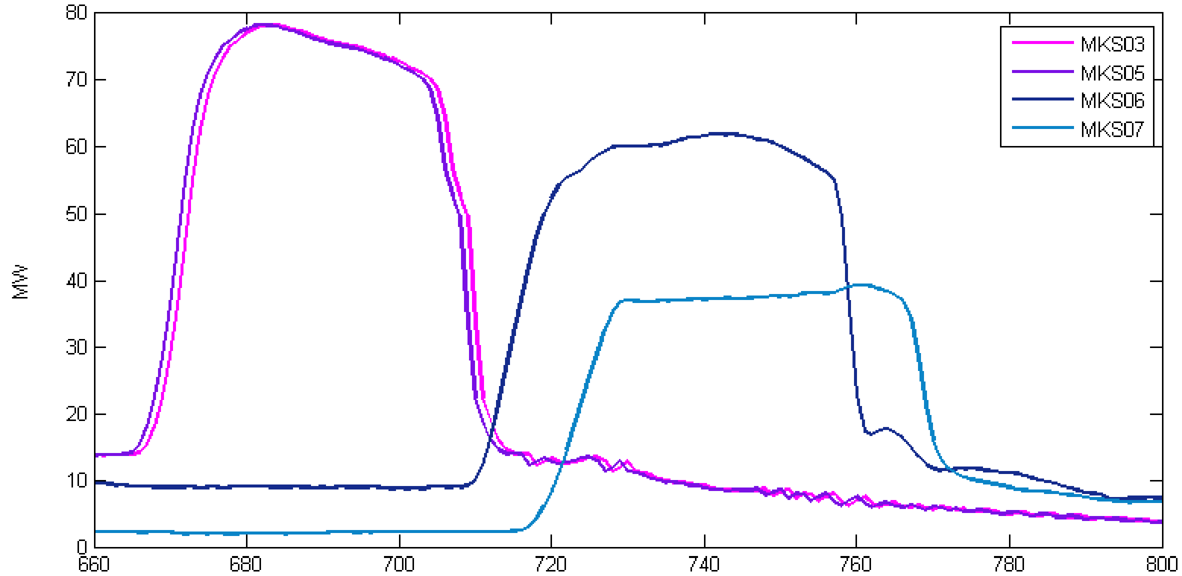
Klystron	ΔP	A	ΔA/A
	deg	MW	%
MKS03	4.16	67.62	4.05%
MKS05	1.97	75.85	7.22%
MKS06	5.18	60.69	5.85%
MKS07	6.24	37.23	2.31%

Klystron	Working area	
	From	To
MKS03	685	705
MKS05	680	700
MKS06	735	755
MKS07	735	755

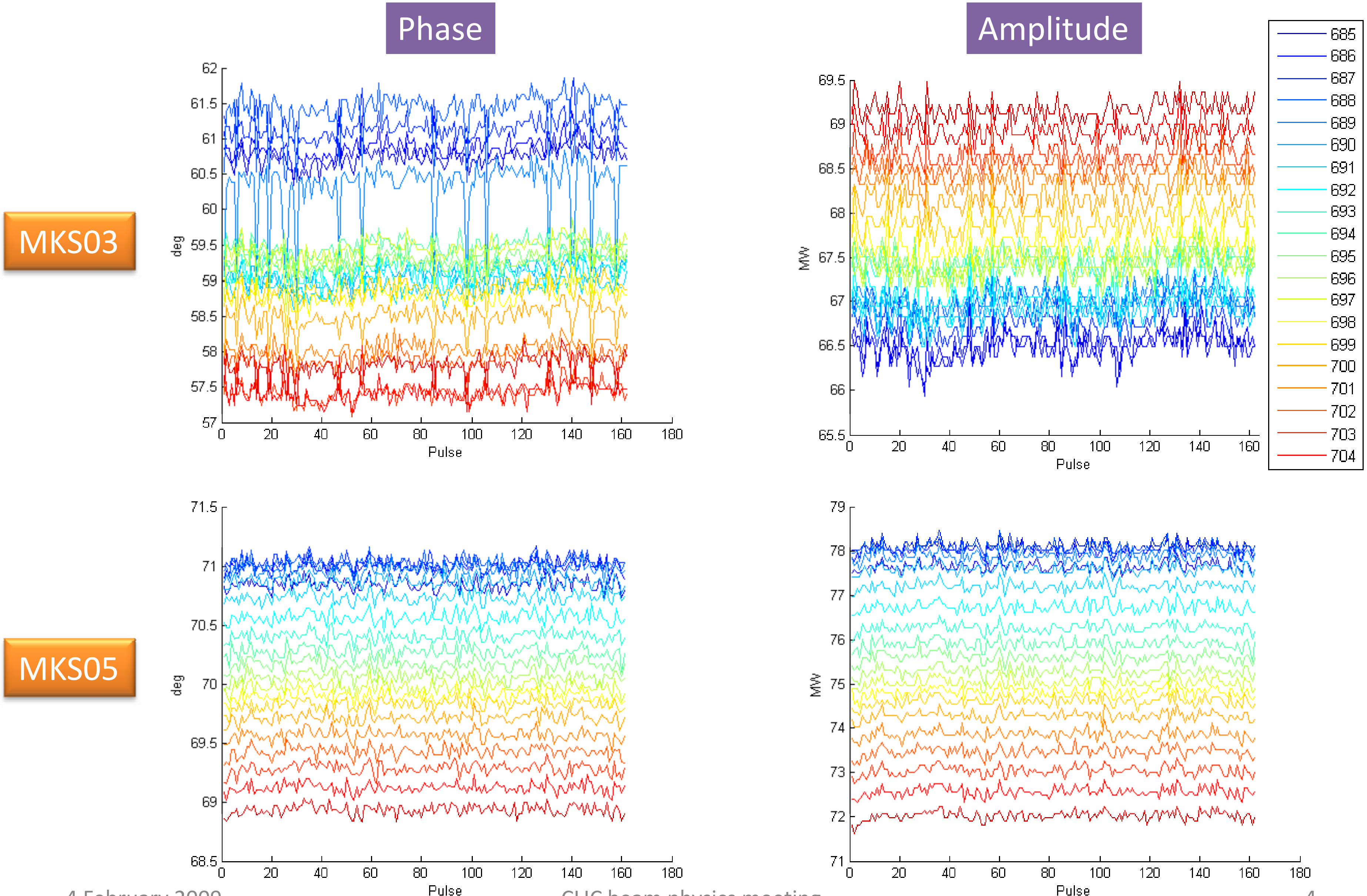
1 time unit = 10.406 ns

Data were taken at 17:31:49 on Dec 12 2008

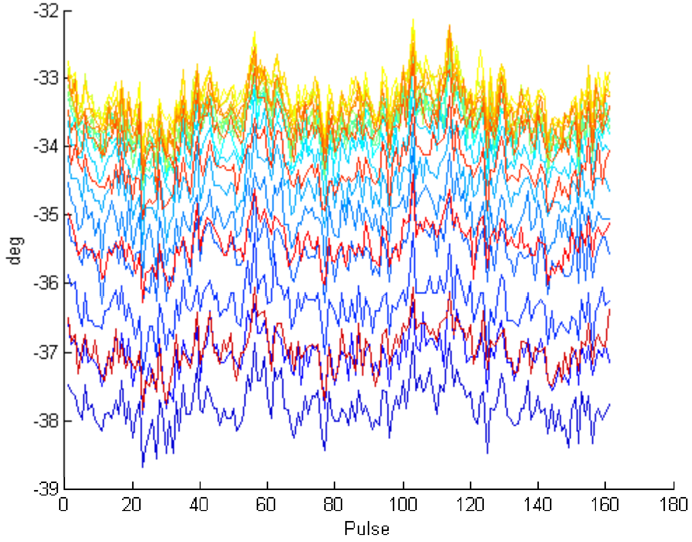
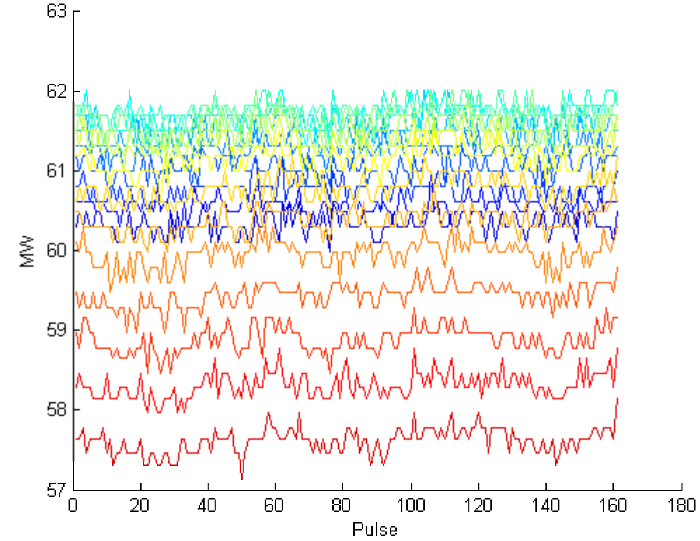
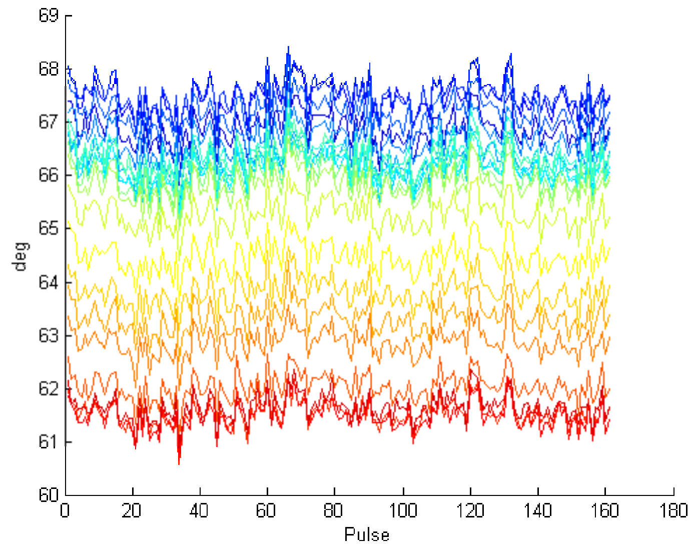
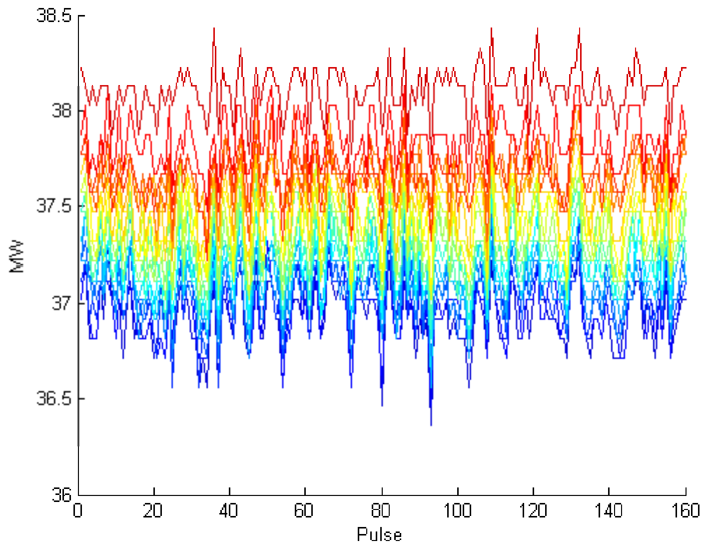




Pulse2Pulse Stability Overview



Pulse2Pulse Stability Overview

	Phase	Amplitude
MKS06		
MKS07		

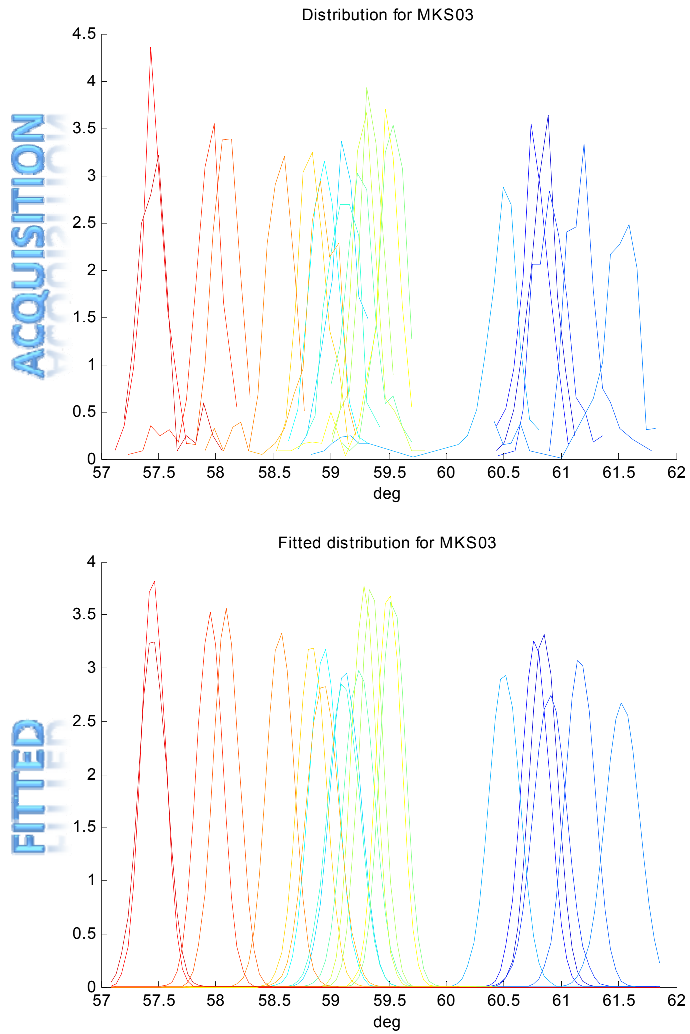
Pulse2Pulse. Probability density function.

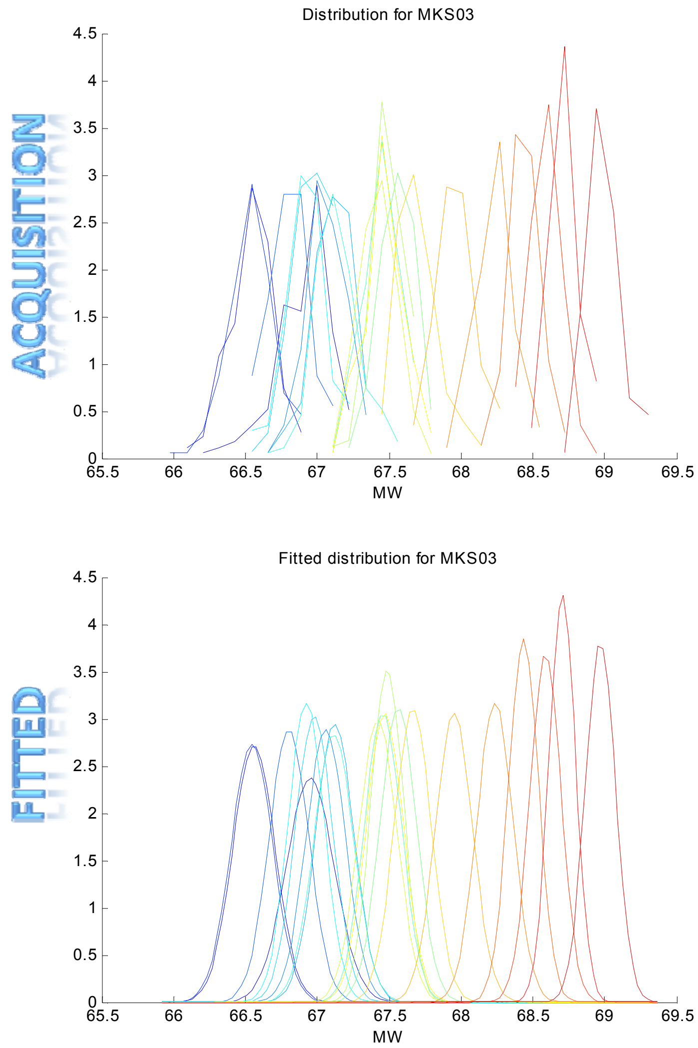
$$\frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

Phase

MKS03

Amplitude



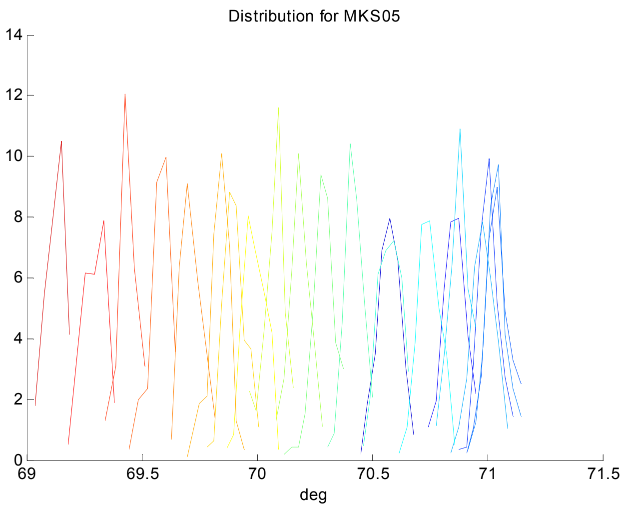


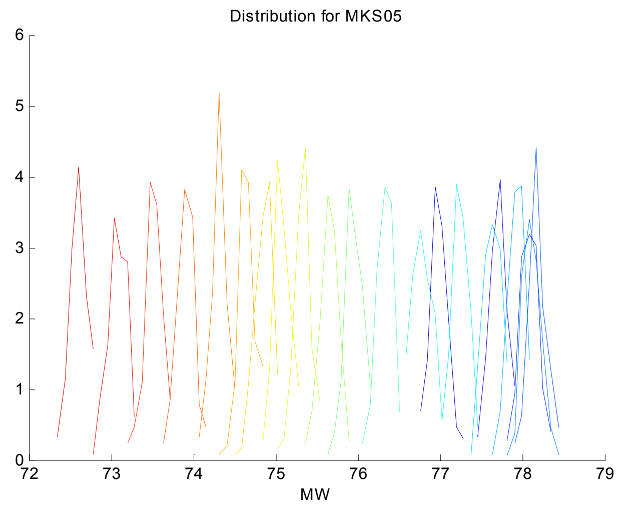
Pulse2Pulse. Probability density function.

$$\frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

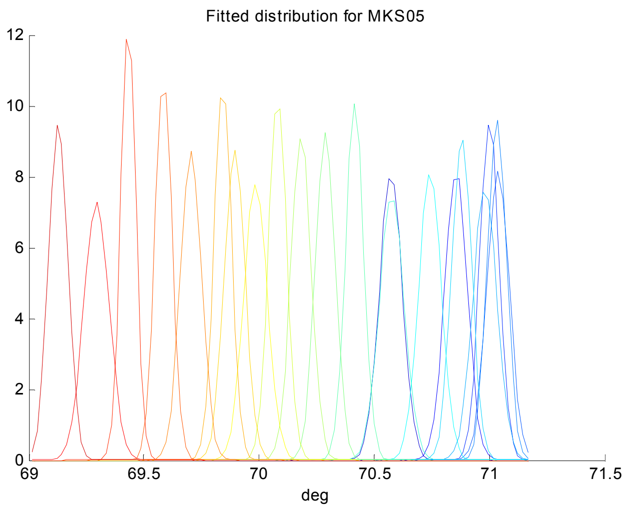
Phase | MKS05 | Amplitude

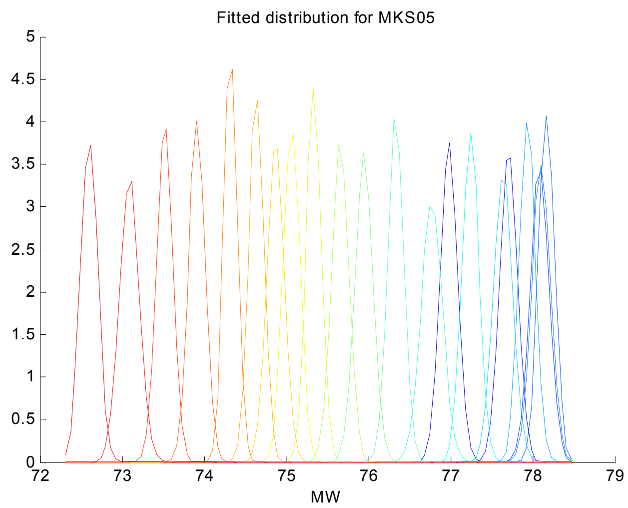
ACQUISITION





FITTED

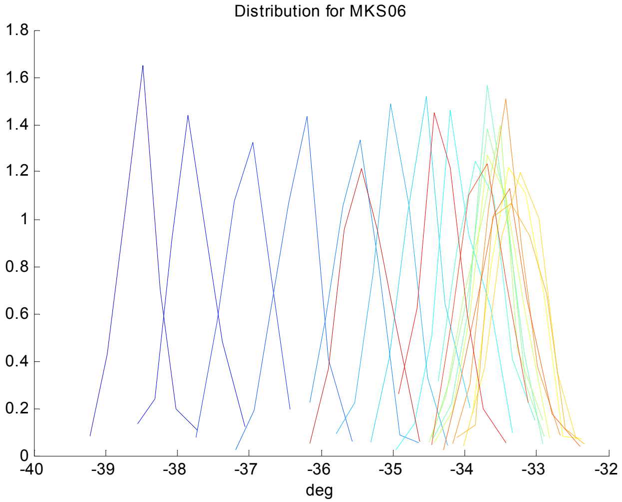


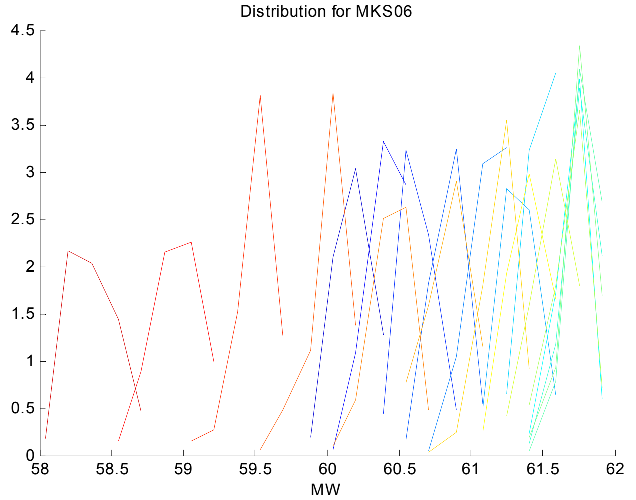


Pulse2Pulse. Probability density function. $\frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$

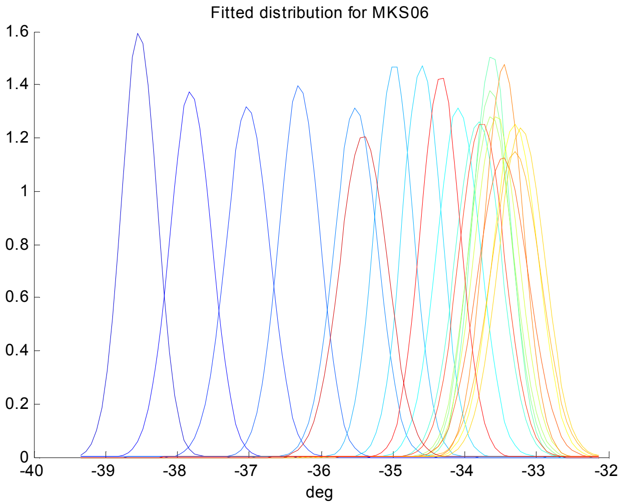
Phase | MKS06 | Amplitude

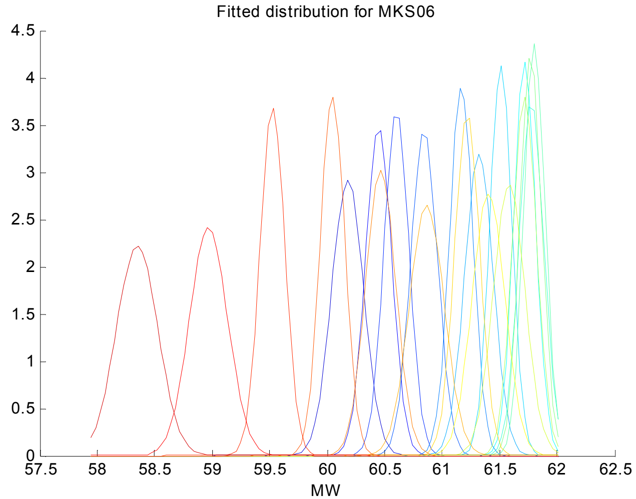
ACQUISITION





FITTED





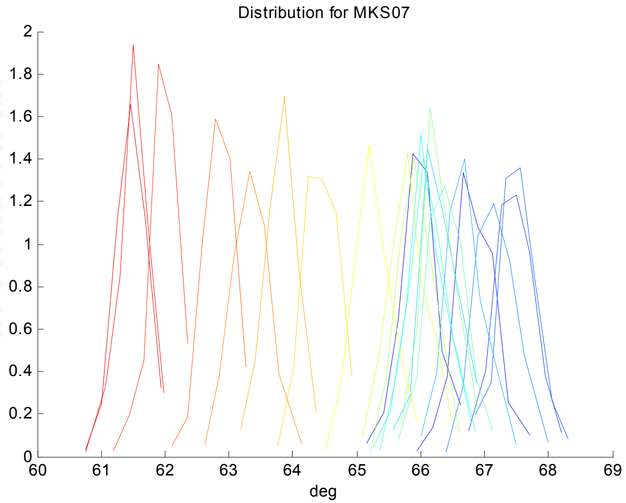
Pulse2Pulse. Probability density function. $\frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$

Phase

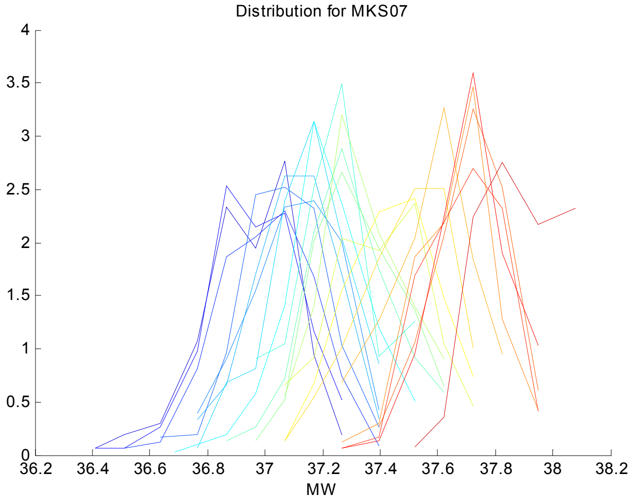
MKS07

Amplitude

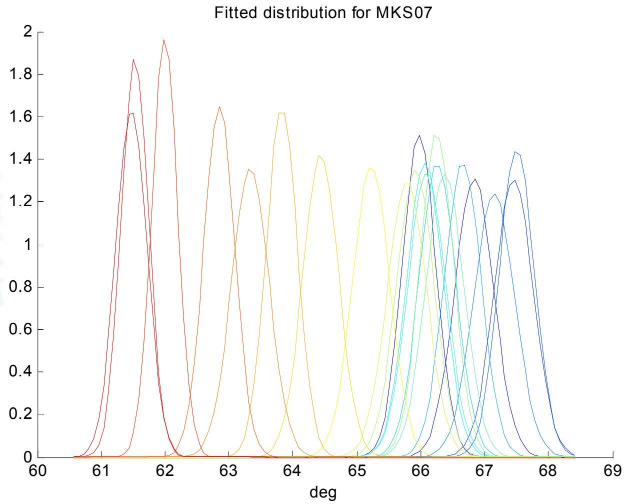
ACQUISITION



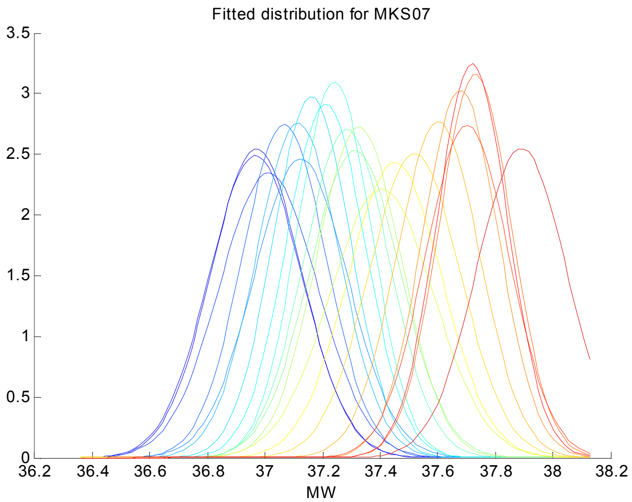
ACQUISITION



FITTED



FITTED

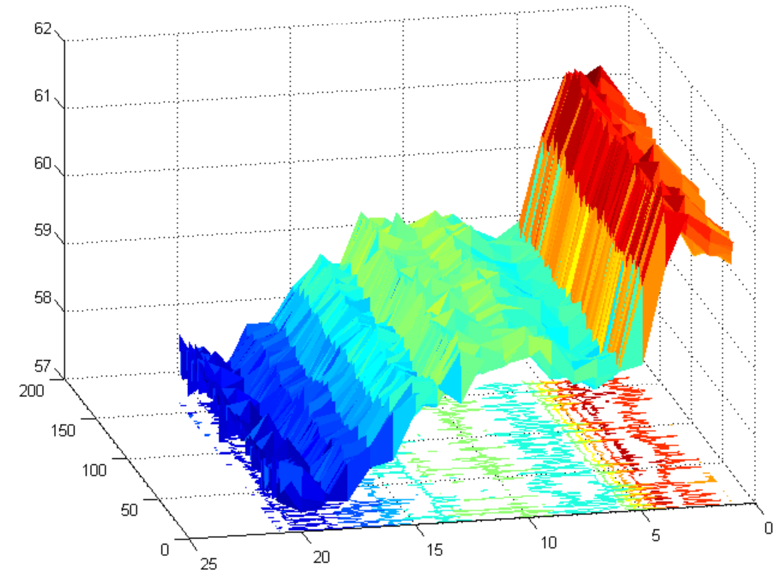


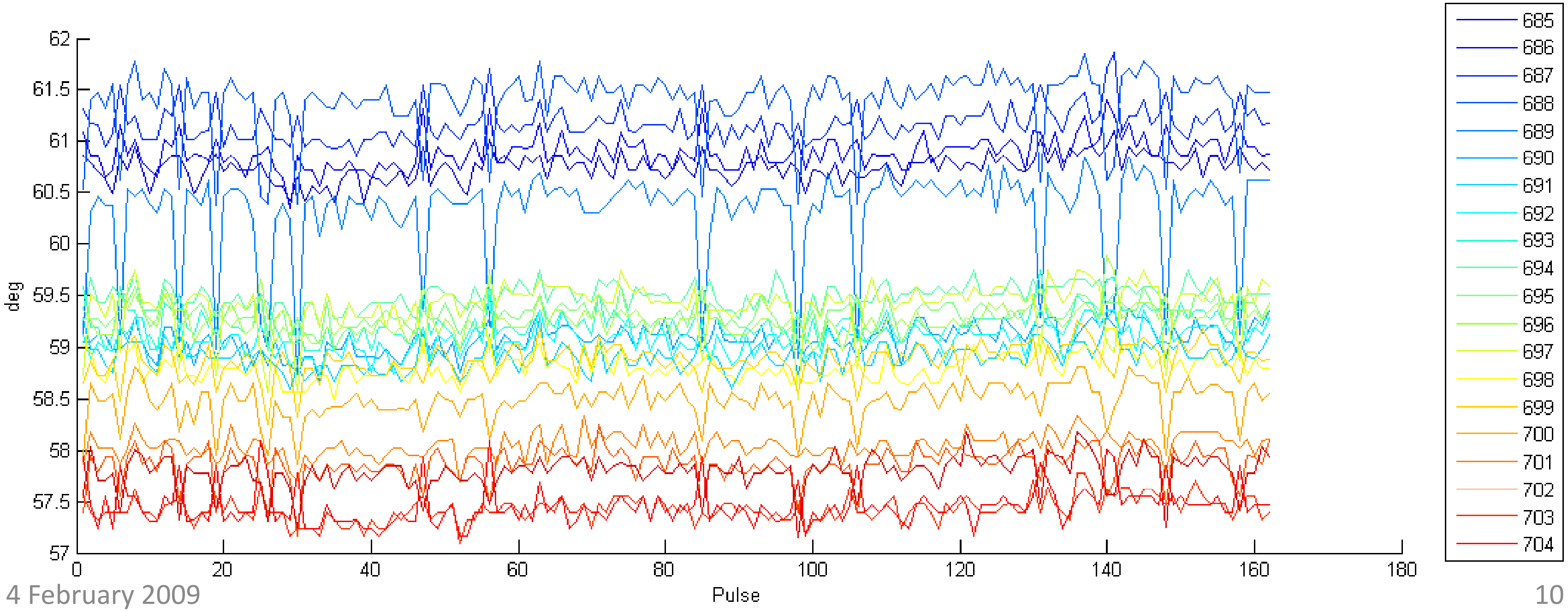
Pulse2Pulse Δμ Stability

MKS03 Phase Analyze

t	685	686	687	688	689	691	692	693	694	695	696
μ	60.8	60.9	61.2	61.5	60.5	59.1	58.9	59.1	59.2	59.5	59.3
σ^2	0.015	0.021	0.017	0.022	0.019	0.018	0.016	0.019	0.018	0.012	0.011

t	697	698	699	700	701	702	703	704	705	706
μ	59.3	59.5	58.8	58.9	58.6	58.1	57.9	57.5	57.4	57.9
σ^2	0.011	0.012	0.015	0.019	0.014	0.013	0.013	0.011	0.015	0.012

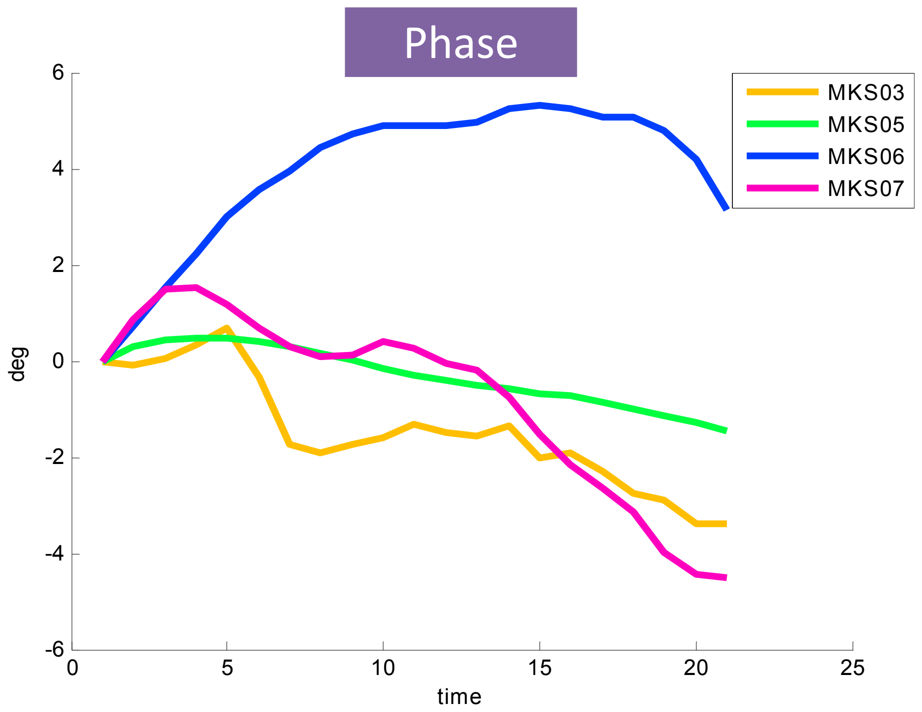


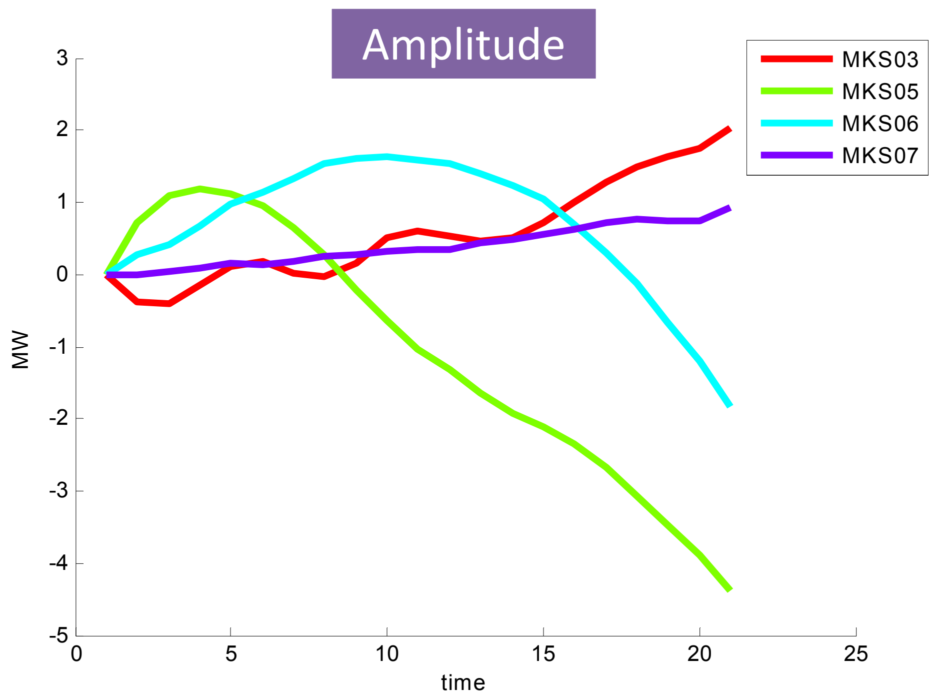


Pulse2Pulse Δμ Stability

Klystron	MKS03		MKS05		MKS06		MKS07	
	deg	*MW*	*deg*	*MW*	*deg*	*MW*	*deg*	*MW*
σ^2_{max}	0.022	0.021	0.003	0.018	0.111	0.032	0.099	0.033
σ^2_{min}	0.011	0.008	7E-04	0.007	0.077	0.008	0.048	8E-04
Δμ	4.082	2.657	2.098	6.106	4.591	4.118	6.058	1.256

Plots of mean values (**Δμ**)

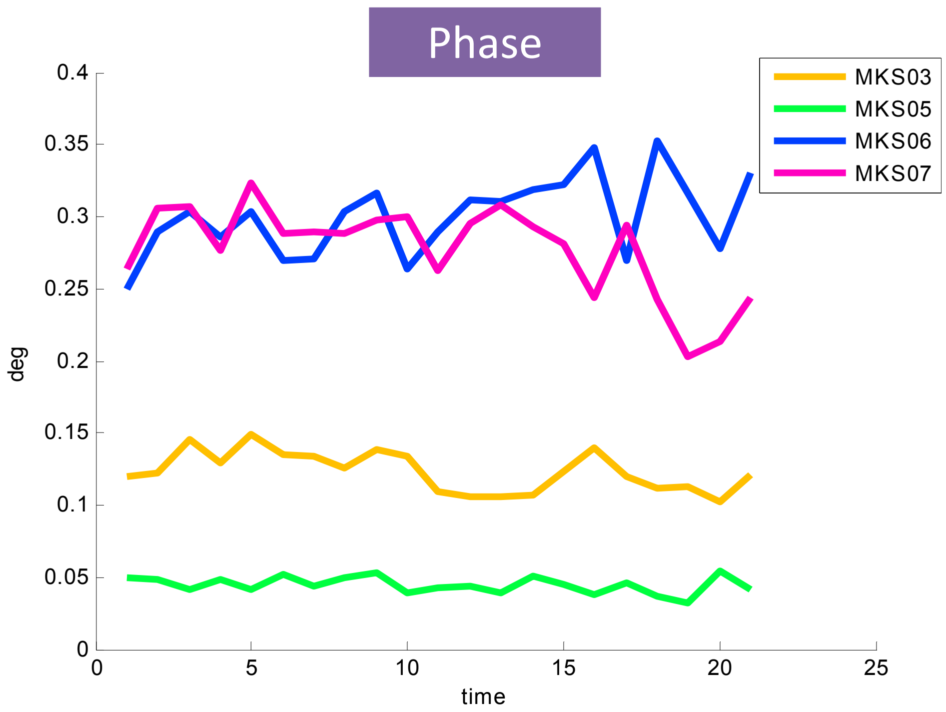


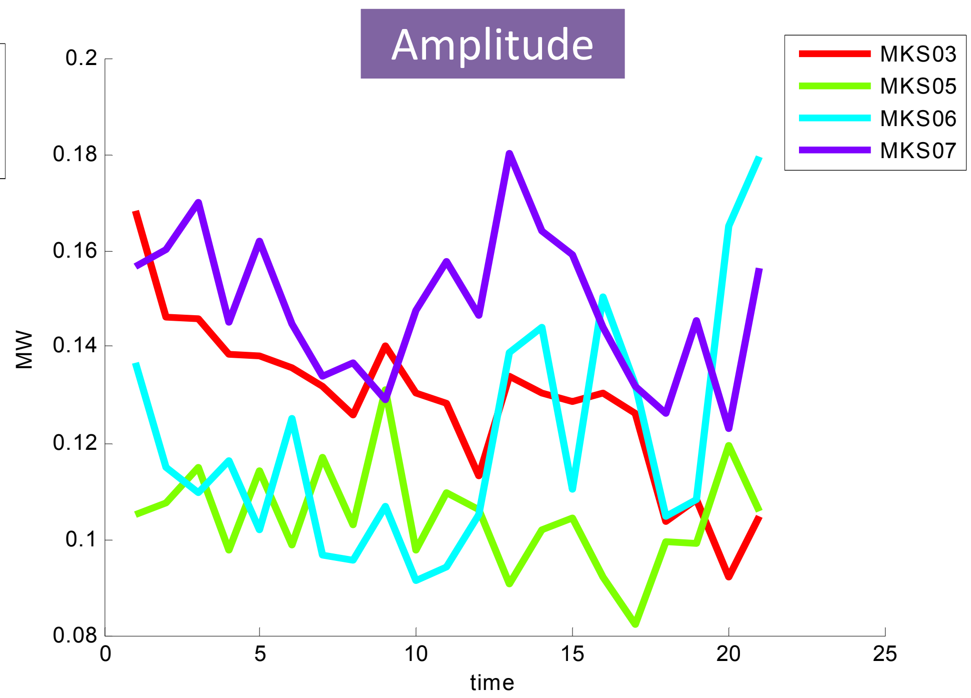


Pulse2Pulse σ^2 Stability

Klystron	MKS03		MKS05		MKS06		MKS07	
	deg	*MW*	*deg*	*MW*	*deg*	*MW*	*deg*	*MW*
σ^2_{max}	0.022	0.021	0.003	0.018	0.111	0.032	0.099	0.033
σ^2_{min}	0.011	0.008	7E-04	0.007	0.077	0.008	0.048	8E-04
Δμ	4.082	2.657	2.098	6.106	4.591	4.118	6.058	1.256

Plots of variance values (**σ**)

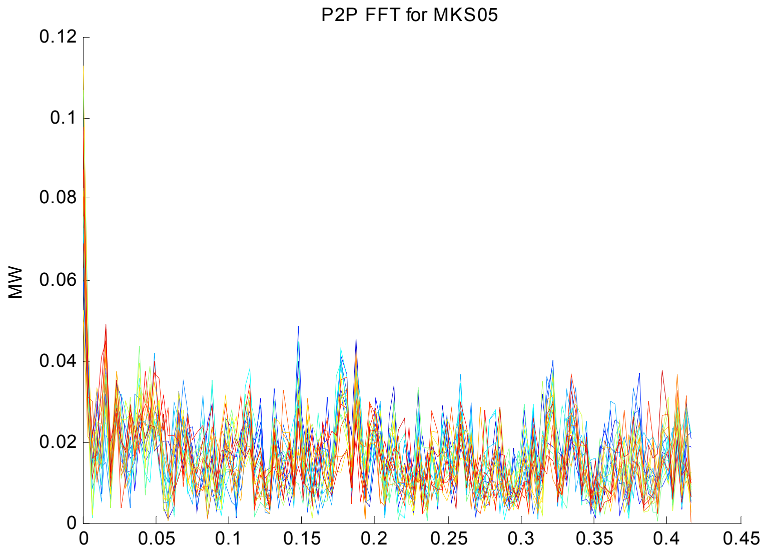


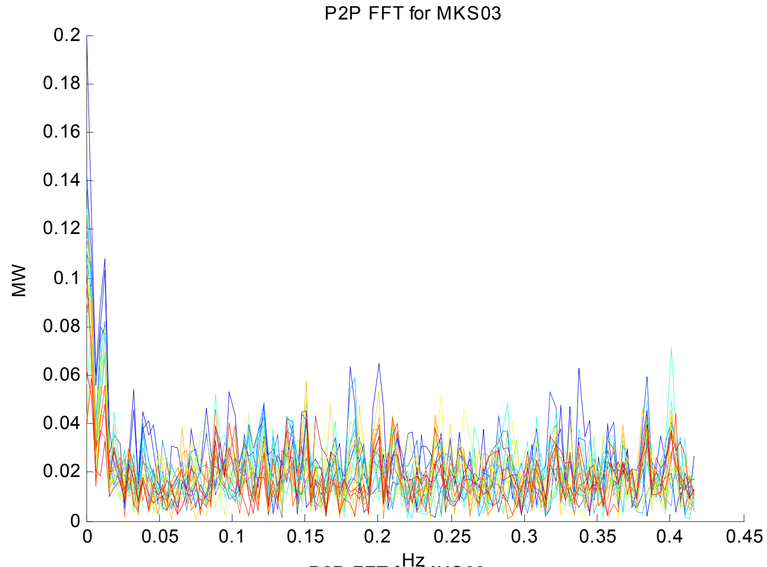


Pulse2Pulse σ^2 FFT

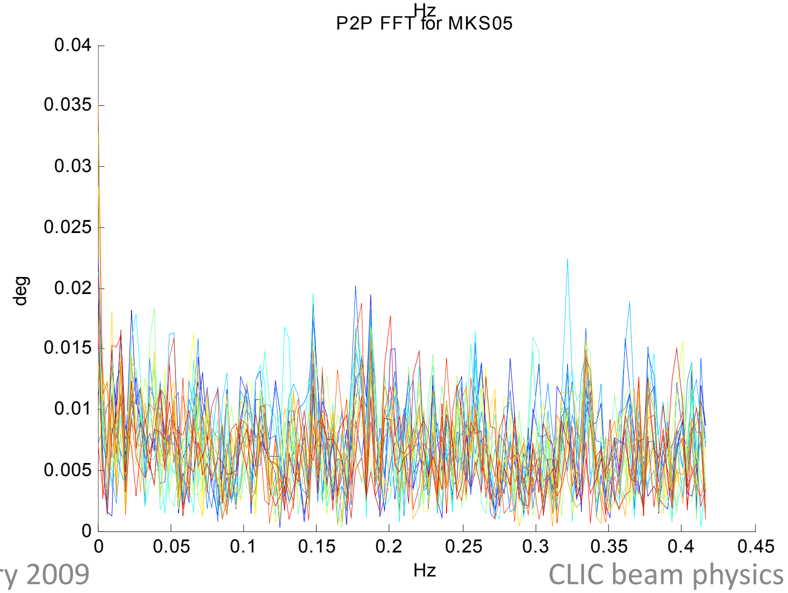
Phase | Amplitude

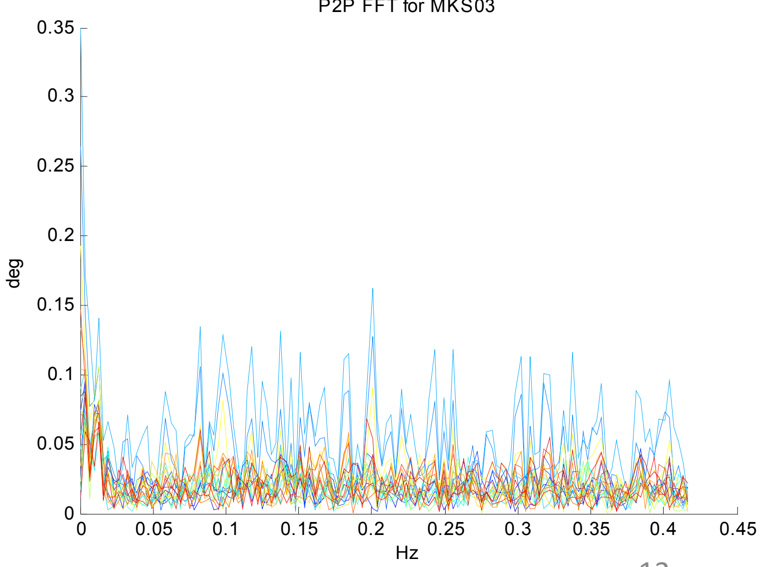
MKS03





MKS05



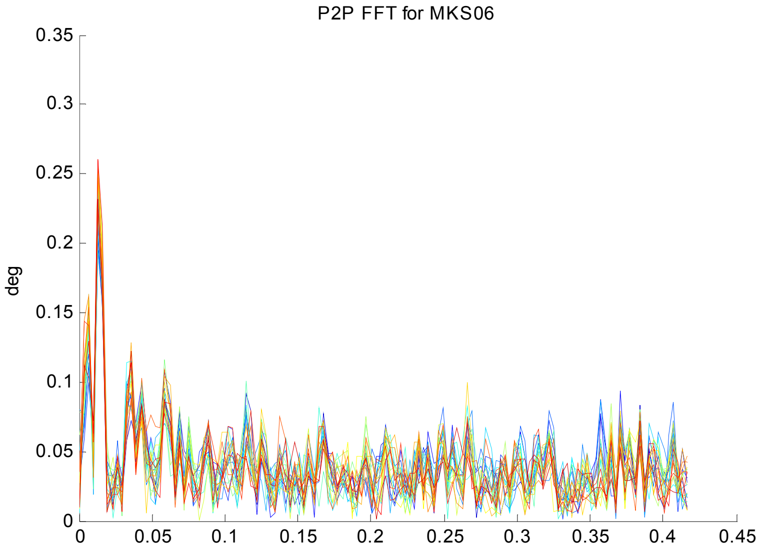


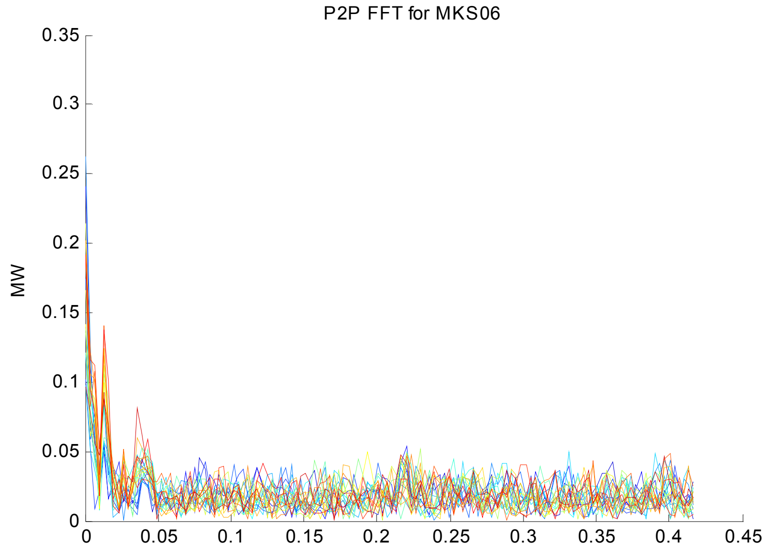
Pulse2Pulse σ^2 FFT

Phase

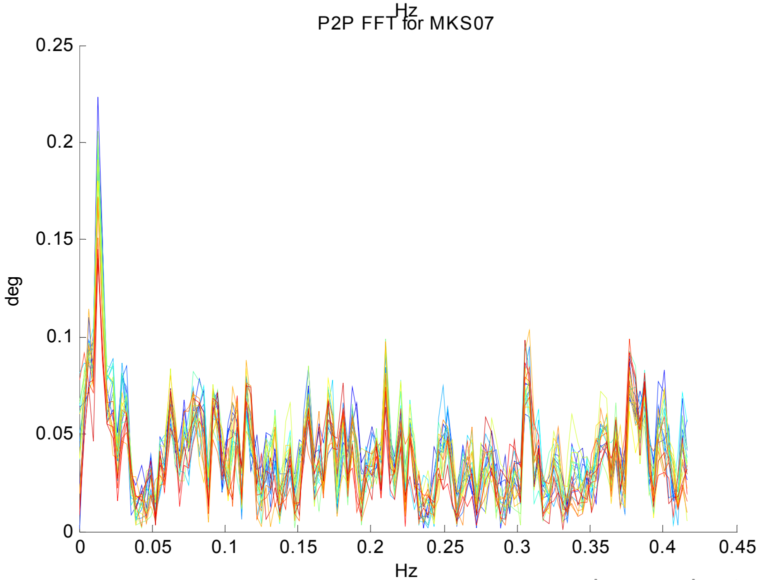
Amplitude

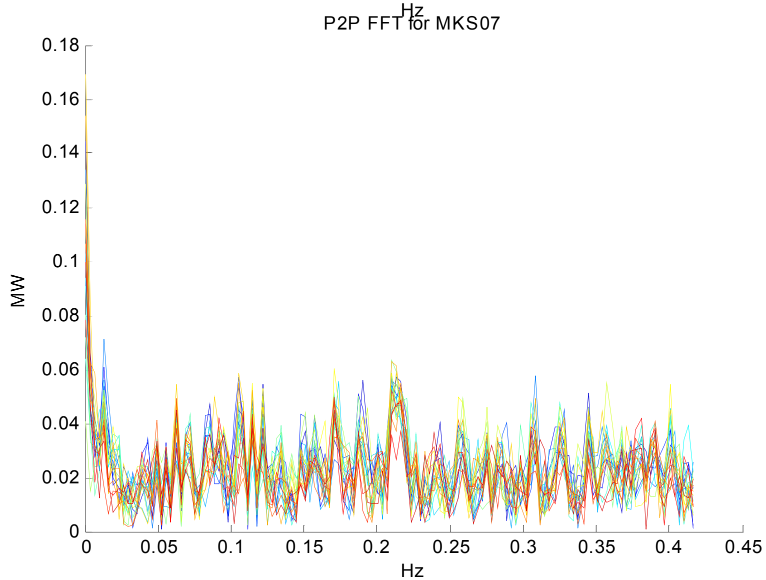
MKS06





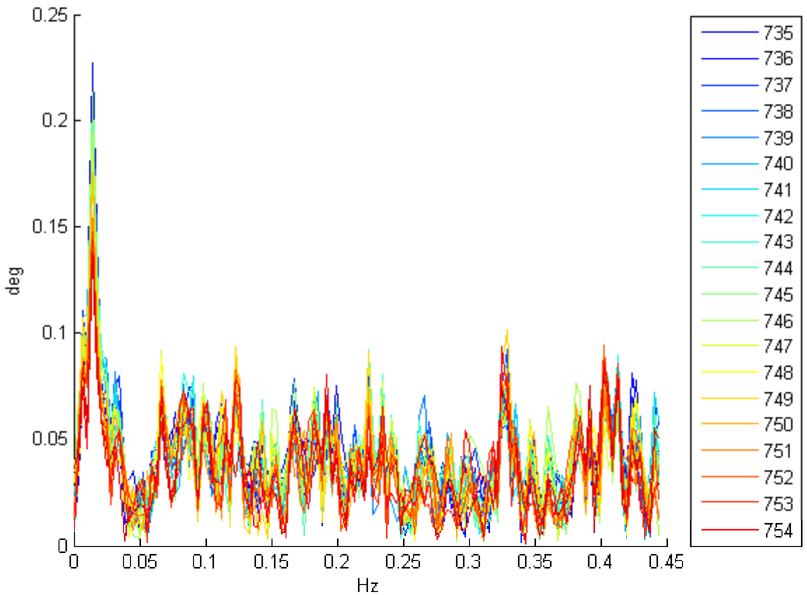
MKS07





Pulse2Pulse σ^2 Stability

Klystron	MKS03		MKS05		MKS06		MKS07	
	deg	*MW*	*deg*	*MW*	*deg*	*MW*	*deg*	*MW*
Main harmonic (Hz)	~~*0.209*~~	~~0.001~~	~~0.148~~	~~0~~	0.014	~~0~~	0.014	~~0.011~~
simple att.	0.067	0.057	0.015	0.05	0.202	0.091	0.135	0.054
complex att.	0.272	0.239	0.088	0.189	0.675	0.189	0.638	0.237
Rest max. Δ	1.338	0.487	0.141	0.234	0.483	0.44	0.378	0.279



MKS07 FFT Analyze of σ^2

t	735	736	737	738	739	740	741	742	743	744	745
Hz	0.0139	0.0139	0.0139	0.0139	0.0139	0.0139	0.0139	0.0139	0.0139	0.0139	0.0139
ΔHz	±0.0035	±0.0035	±0.0035	±0.0035	±0.0035	±0.0035	±0.0035	±0.0035	±0.0035	±0.0035	±0.0035
simple att. (deg)	0.227	0.1931	0.1944	0.2092	0.2032	0.1923	0.2008	0.1985	0.2106	0.2042	0.2132
max att.(deg)	0.8387	0.659	0.6839	0.8303	0.845	0.6804	0.7973	0.7587	0.7965	0.6533	0.7184
err. (deg)	0.3778	0.2727	0.2868	0.2269	0.26	0.262	0.2596	0.2194	0.259	0.2491	0.2858

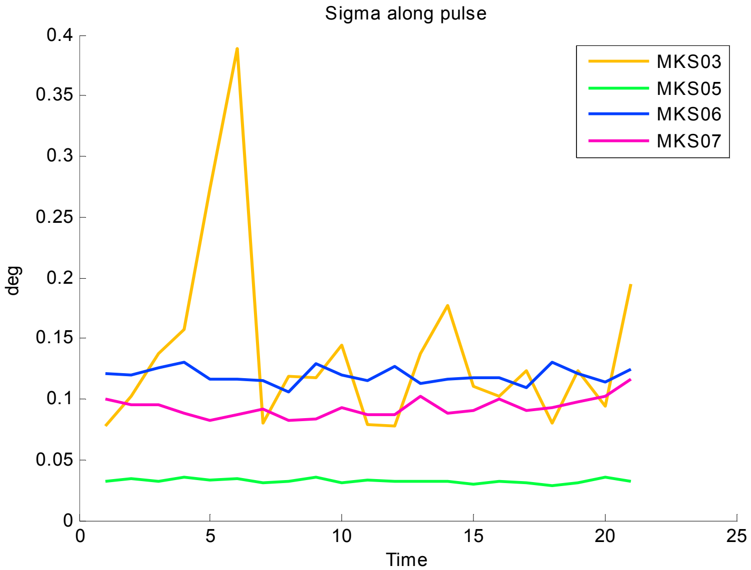
t	746	747	748	749	750	751	752	753	754	755
Hz	0.0139	0.0139	0.0139	0.0139	0.0139	0.0139	0.0139	0.0139	0.0139	0.0139
ΔHz	±0.0035	±0.0035	±0.0035	±0.0035	±0.0035	±0.0035	±0.0035	±0.0035	±0.0035	±0.0035
simple att. (deg)	0.1944	0.1855	0.1719	0.1739	0.1755	0.154	0.1471	0.1471	0.1439	0.1346
max att.(deg)	0.6759	0.6727	0.6677	0.6375	0.8864	0.734	0.8344	0.8155	0.6981	0.6527
err. (deg)	0.2841	0.2444	0.2097	0.2776	0.2213	0.2414	0.2766	0.3266	0.2947	0.3202

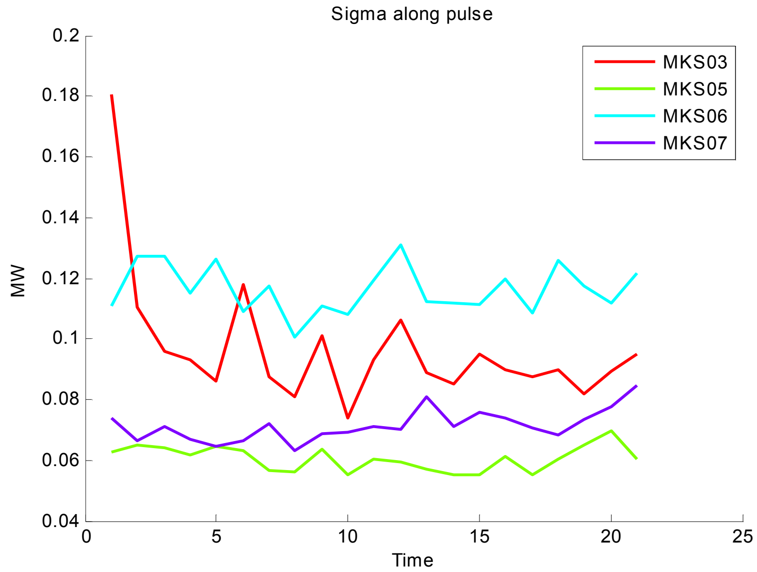
σ-values after subtraction of Δμ and harmonics

Phase

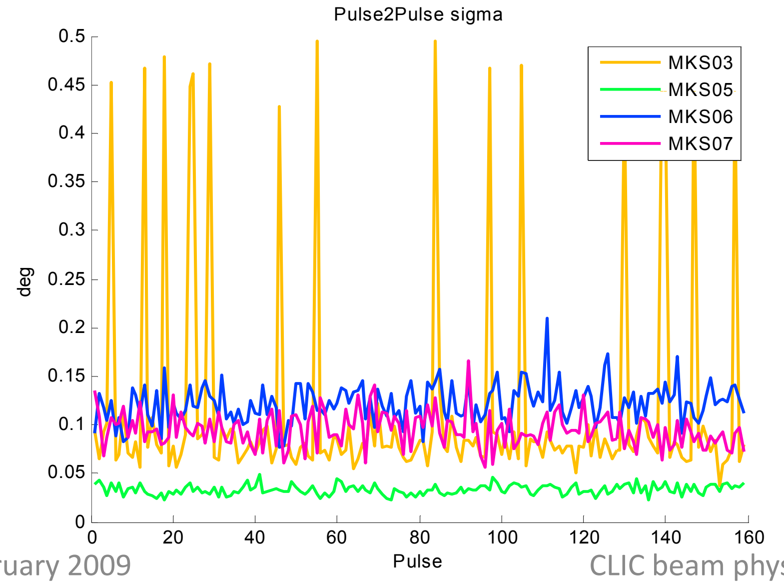
Amplitude

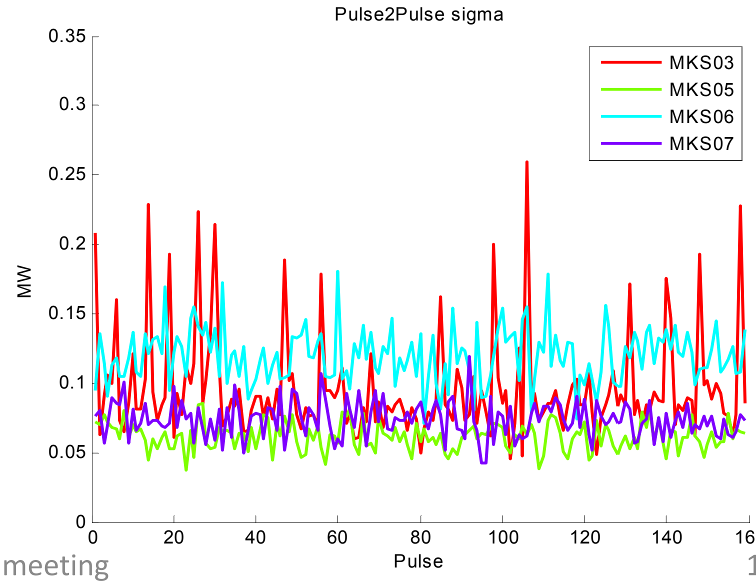
σ along pulse





Pulse2Pulse σ



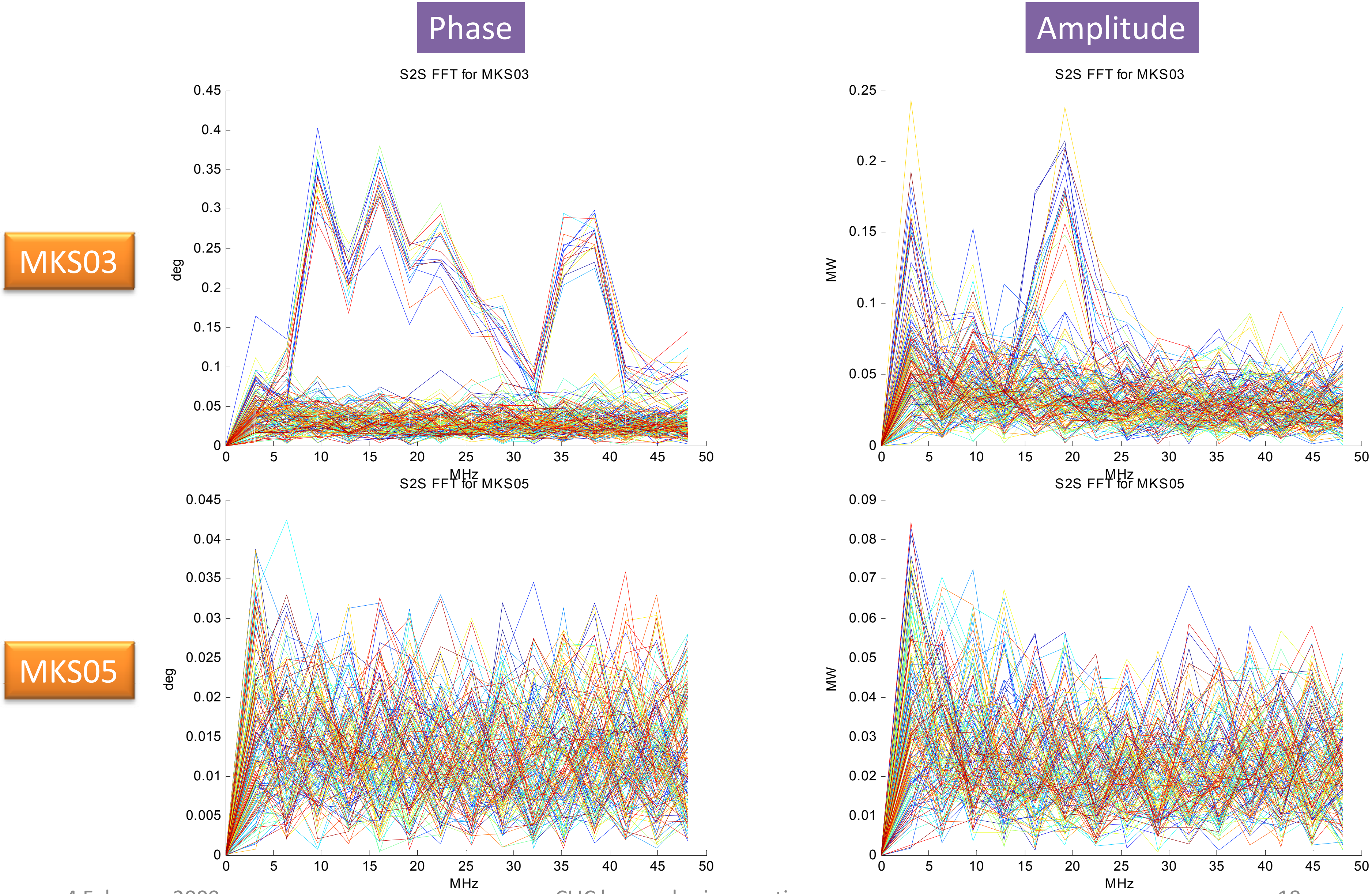


Fast pulse2pulse feed-back conditionality

Klystron	MKS03		MKS05		MKS06		MKS07		Total	
	deg	MW	deg	MW	deg	MW	deg	MW	deg	MW
Max. Δ	4.7744	3.560306	2.33571	6.852	6.53312	4.8818	7.85	2.0705	21.49323	17.36461
P2P Δμ FD	85.50%	74.63%	89.82%	89.11%	70.27%	84.35%	77.17%	60.66%	78.30%	81.41%
P2P σ^2 FD	5.69%	6.71%	3.75%	2.76%	10.34%	3.86%	8.12%	11.44%	7.78%	4.91%
Rest Δ	28.02%	13.67%	6.05%	3.42%	7.40%	9.02%	4.81%	13.46%	10.89%	8.29%

- Klystron phase can be adjusted to the flat top by 70-90% applying a fast pulse-to-pulse feedback based on the control of phase waveform
- Klystron power can be adjusted to the flat top by 60-90% applying a fast pulse-to-pulse feedback based on the control of amplitude waveform

Pulse FFT for tigidou stabilization

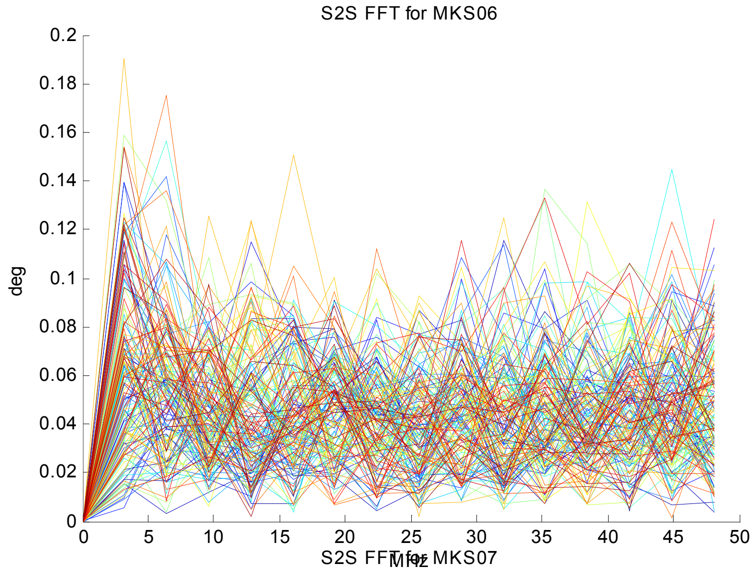


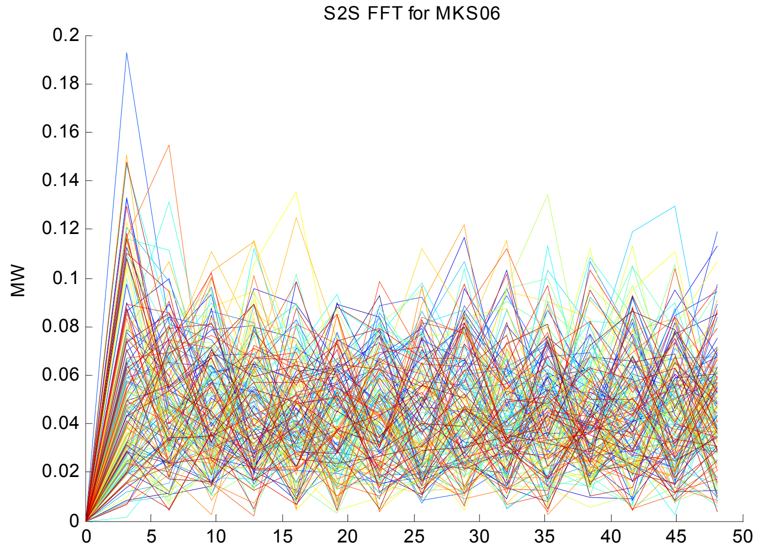
Pulse FFT for tigidou stabilization

Phase

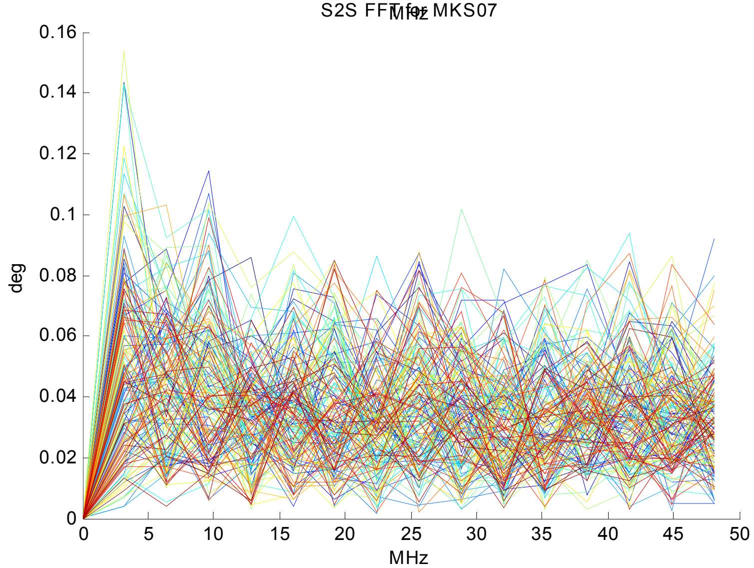
Amplitude

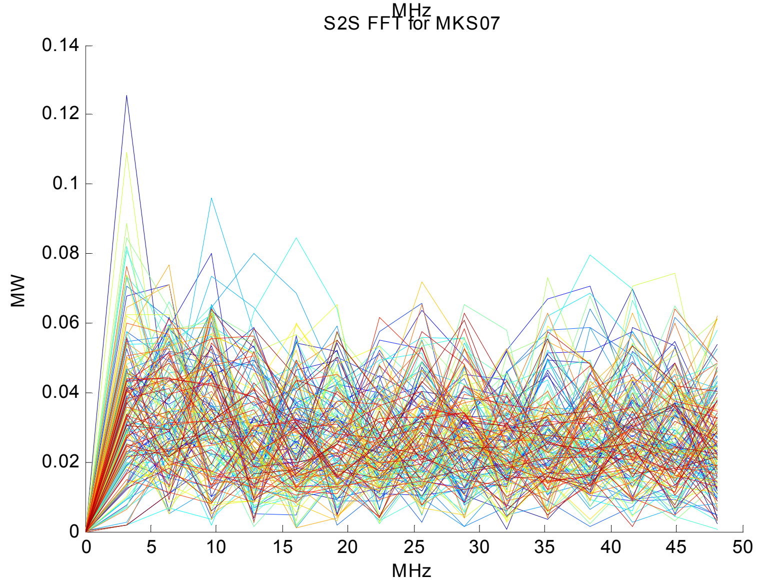
MKS06



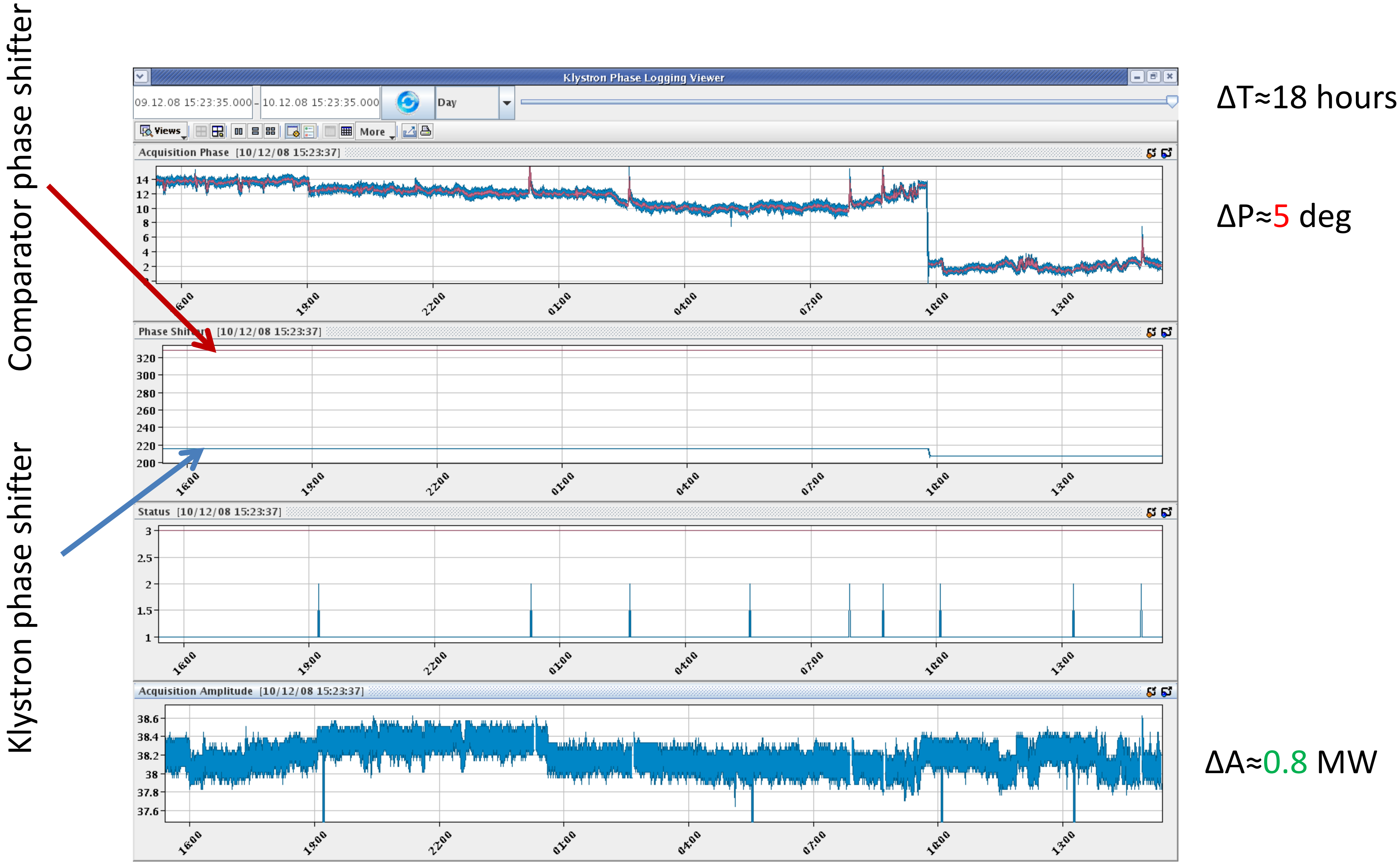


MKS07

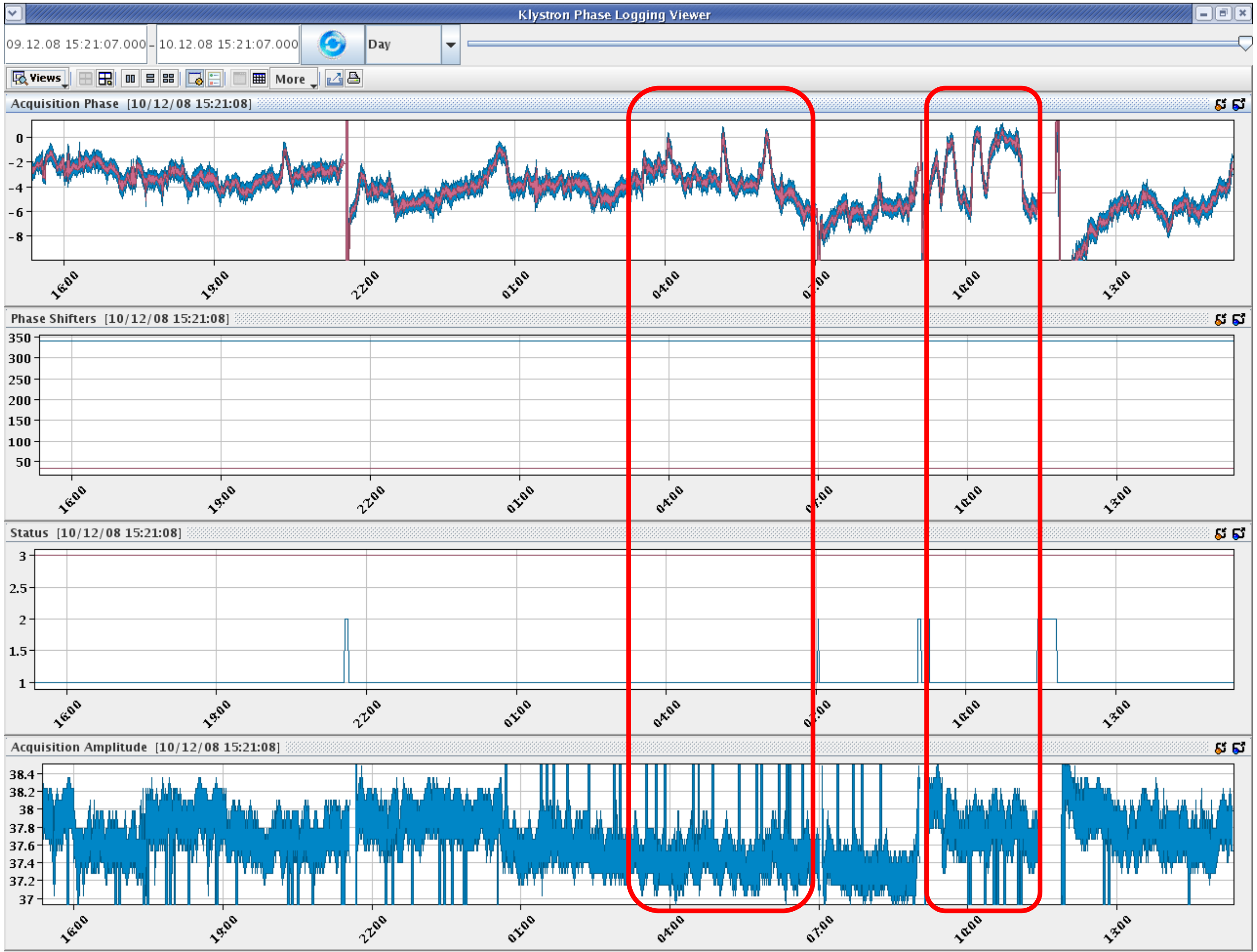




MKS05 phase and amplitude long term changes



MKS06 phase and amplitude long term changes

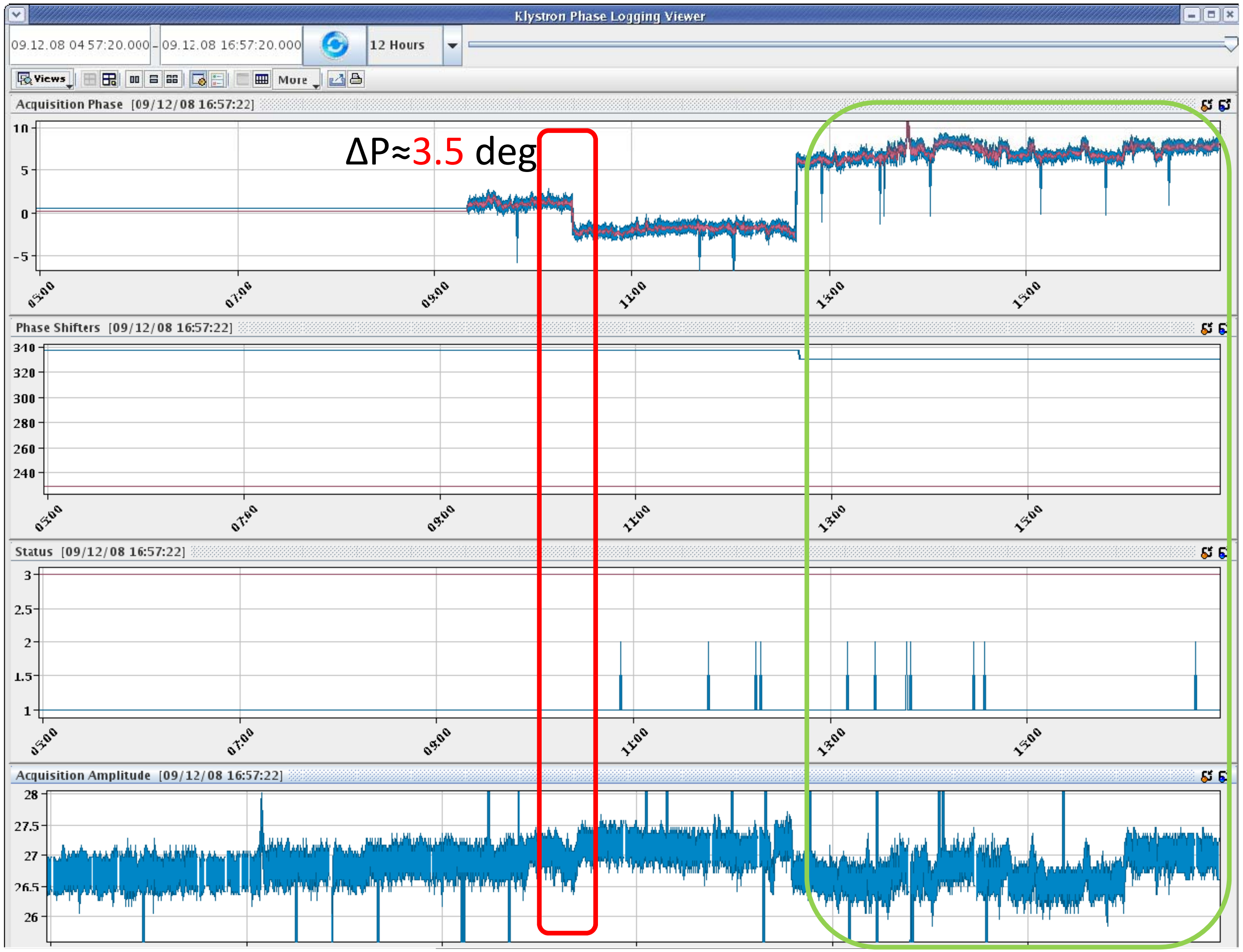


ΔT≈19 hours

ΔP≈8 deg

ΔA≈1.2 MW

MKS07 phase and amplitude long term changes

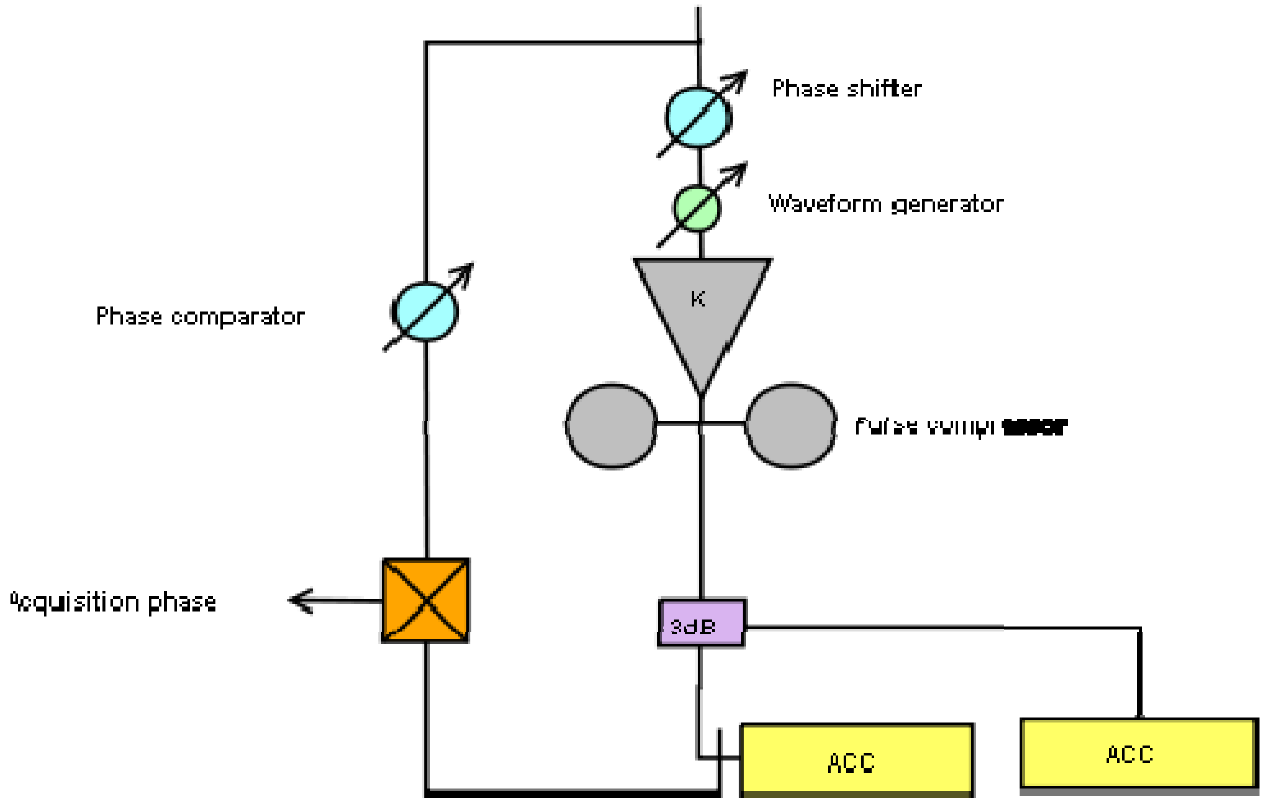


ΔT≈4.5 hours

ΔP≈3.5 deg

ΔA≈1.2 MW

Slow Pulse2Pulse Phase Stabilization. Phase loop.



Klystron phase loop layout was prepared by J. Sladen in order to compensate slow RF phase variation in accelerating structures due to klystron output phase instabilities along day.

Slow Pulse2Pulse Phase Stabilization. EMA.

Since the fast pulse2pulse phase deviation approximately equals to the slow phase variation, an acquisition phase averaging is required. An exponential moving average (EMA) was introduced:

$$ema_i = \begin{cases} \sum_{j=1}^{i} p_j & , i \le n, \\ k\, ema_{i-1} + (1-k)\, p_i & , i > n, \end{cases}$$

where $\{p_j\}$ is the phase acquisition values, n is a integer and 0 < k < 1. In the CTF case the sampling rate of $\{p_j\}$ is ~1 sec. Normally, $k = \frac{n-1}{n}$

The phase error at any acquisition moment can be introduced in the following way using a Fourier series:

$$ema_i - p \cong \mathcal{N}(\mu, \sigma^2) + \varepsilon + \sum_{m=M_S}^{\infty} \Delta p_m \sin(f_m i + \varphi_m) \cong \mathcal{N}(\mu, \sigma^2) + \varepsilon + \varepsilon_S$$

$$M_F < n < M_S$$

Fast variation   Other errors   Slow variation

Thus, $ema_i - p \approx \varepsilon_N + \varepsilon + \varepsilon_S, \quad n < i \ll \frac{1}{f_{M_S}}, \quad |\varepsilon_S| \lesssim \sum_{m=M_S}^{\infty} i \Delta p_m f_m, \quad |\varepsilon_N| \lesssim \frac{max\{p_j\} - min\{p_j\}}{n}$

In order to archive a small error, the number *n* must be between the main slow and fast harmonics. And the number ε limits the quality of a feed-back, which will be based on the EMA.

Slow Pulse2Pulse Phase Stabilization. EMA.

Acquisition phase is red. EMA is blue.

Slow Pulse2Pulse Phase Stabilization. Absolute control gain.

$$|\varepsilon_{\mathcal{N}} + \varepsilon + \varepsilon_S| \leq |\varepsilon_{\mathcal{N}}| + |\varepsilon| + |\varepsilon_S| \leq \frac{gain}{2} \longrightarrow \frac{\Delta p}{n} + \varepsilon + n\Delta p_{M_S} f_{M_S} \leq \frac{gain}{2}$$

$$\Delta p = max\{p_j\} - min\{p_j\}$$

Sufficient conditions

$$|gain - 2\varepsilon| > 4\sqrt{\Delta p \Delta p_{M_S} f_{M_S}}$$

$$0.3 < gain_{min} < 0.6$$

$$n < \frac{\left(\frac{1}{2}gain - \varepsilon\right) + \sqrt{\left(\frac{1}{2}gain - \varepsilon\right)^2 - 4\Delta p \Delta p_{M_S} f_{M_S}}}{2\Delta p_{M_S} f_{M_S}}$$

$$n_{min} \approx 90$$

Slow Pulse2Pulse Phase Stabilization.

The gain is a constant of 1 deg, n=100

Data were taken in 2006

Thank you for your attention