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PSI

Christopher Gough :: RF Section:: Paul Scherrer Institut

Jitter Measurement to 10ppm Level for Pulsed Power Amplifiers 3-12 GHz

LLRF Workshop, Barcelona, 16-19 October 2017

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Introduction

Amplifier Measurement System and Typical Results

Examples of Poor Amplifier Design

Summary for Amplifier Users

Introduction

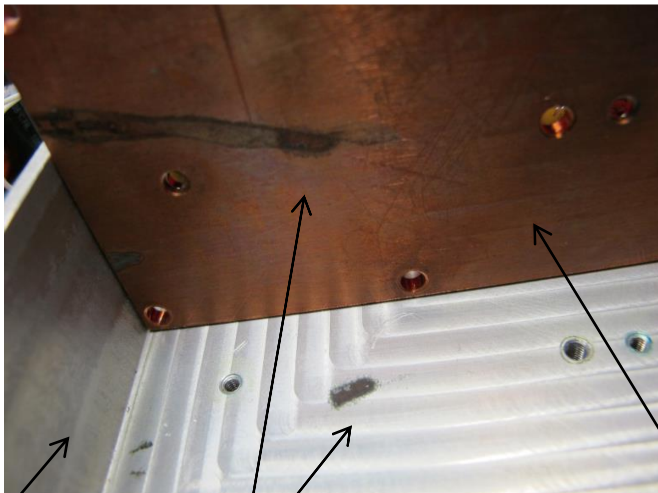
For the SwissFEL project at the Paul Scherrer Institute, pulsed solid state power amplifiers of the 500 W / 3 µs / 100Hz class for driving the klystrons were required. For these amplifiers, a stable interferometer system was developed to measure the residual RF jitter levels to <10 ppm (parts per million) and <10 µrad (0.573 millidegree RF) rms.

[0] "*Jitter Measurement to 10ppm Level for Pulsed Power Amplifiers 3-12GHz*",Gough C., Dordevic S., Paraliev M., THPIK096, IPAC 2017, Copenhagen

[5] *"Comparison of High Resolution Balanced and Direct Conversion Measurement of SwissFEL Resonant Kicker Amplitude*", Paraliev M. and Gough C., IEEE Pulsed Power Conference, Austin, USA, May 31 2015-June 4 2015

Two Main Causes of Power Amplifier Jitter

1. Erratic RF contact

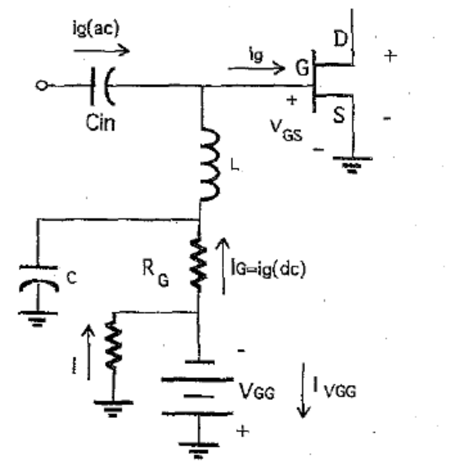


Aluminium housing

Discharge between mating surfaces

Copper palette –
RF circuit board on upper surface,
Screwed against housing on lower surface

2. Flicker noise in gate bias of RF transistors



The RF levels are high, the signal of interest is narrow band so <u>additive</u> thermal noise at RF is not the main concern

Jitter in this application is caused by gain changes, that is <u>multiplicative</u>.

With poor amplifier design, jitter measurements are never definitive because of erratic electrical contact

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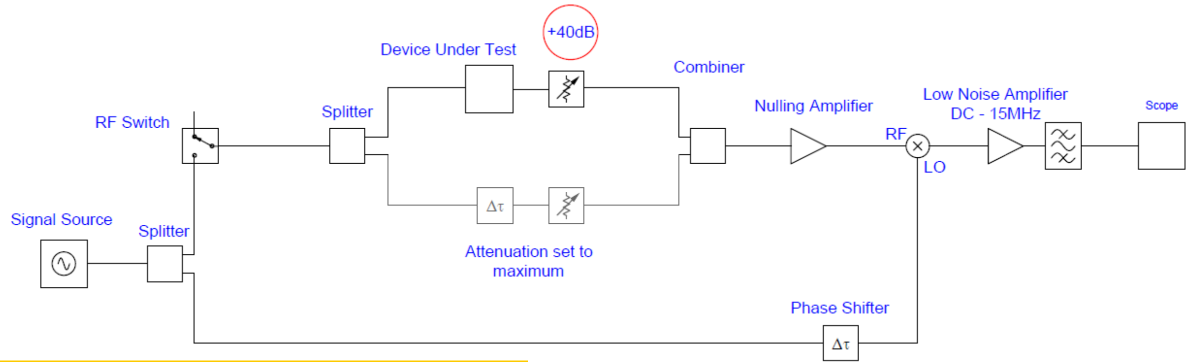
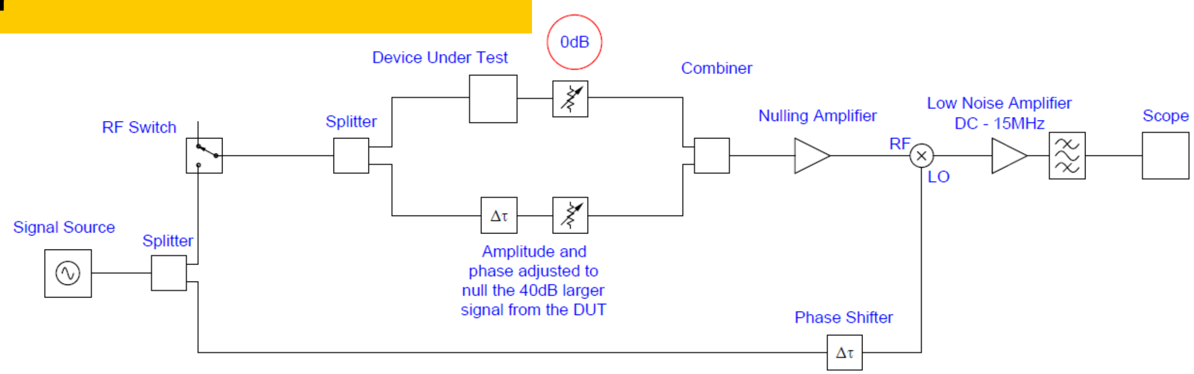
AMS - Amplifier Measurement System

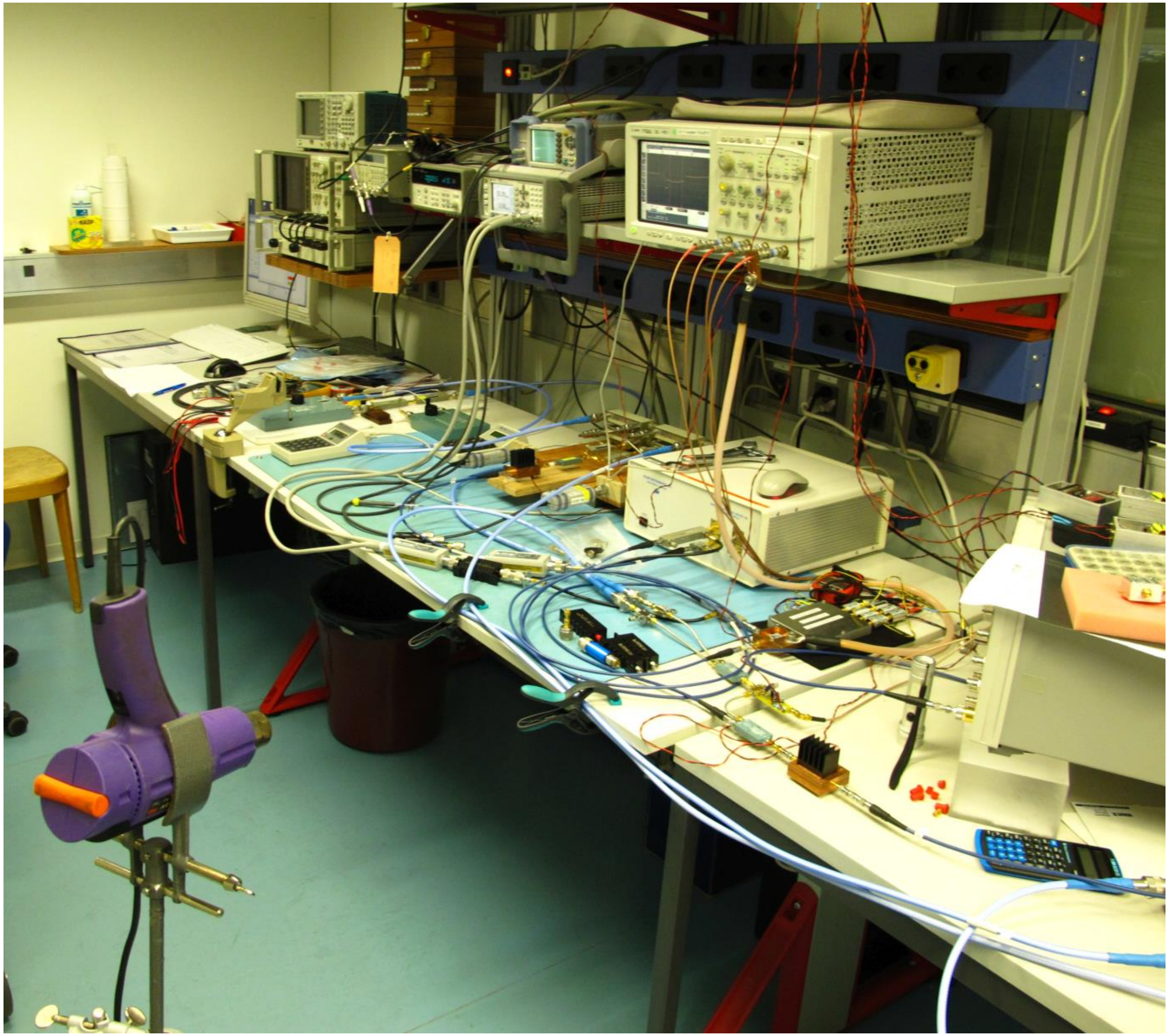


Phase A
Step Phase Shifter through >360° RF
Record positive and negative signal amplitudes on scope – this gives the scale factor

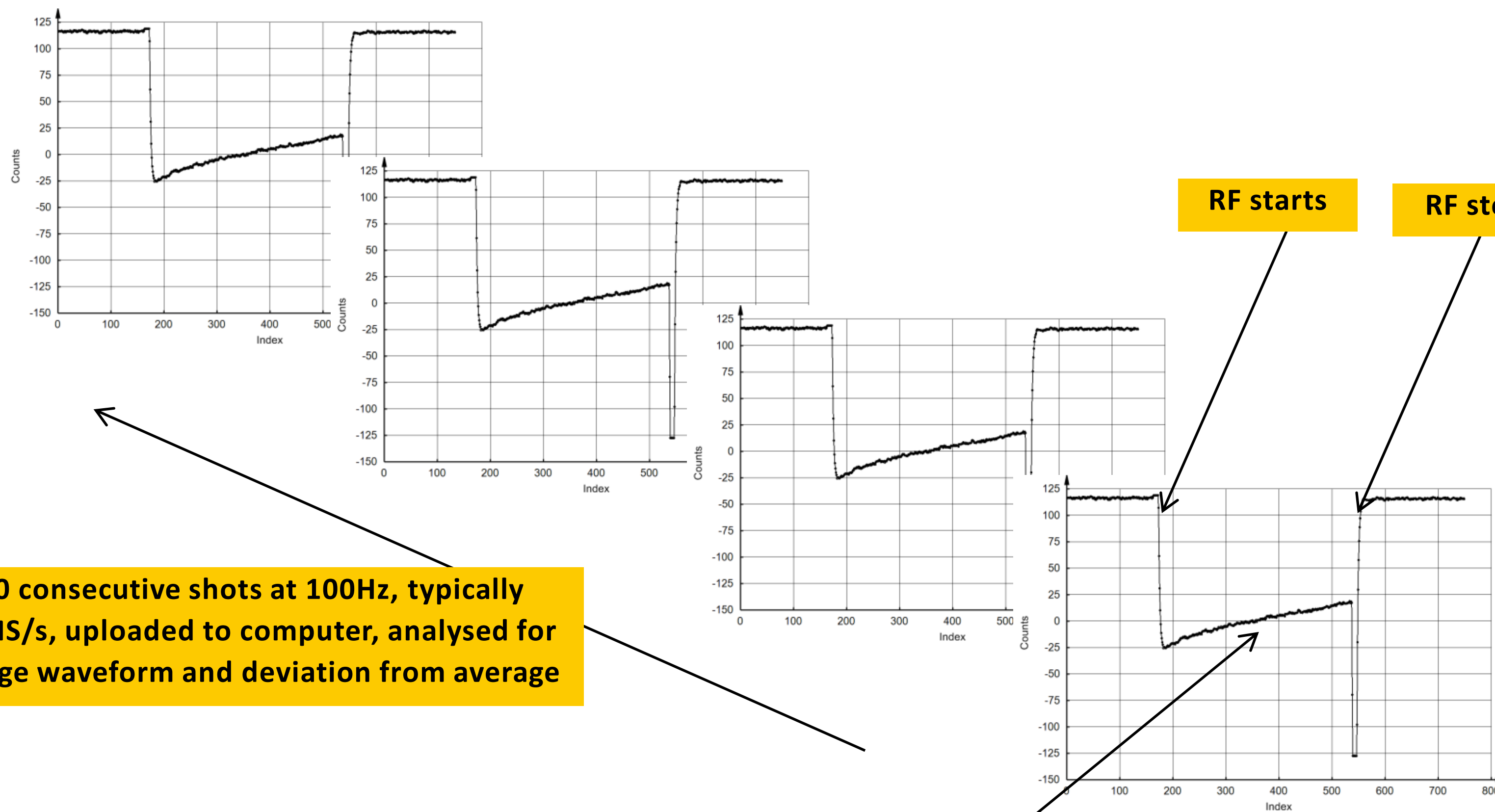


Phase B
Make the interferometer signal larger by 40dB (100 times voltage)
Use fine amplitude and phase adjustments to null interferometer
Step Phase Shifter through >360° RF
Download 100 consecutive scope waveforms and analyse for jitter

AMS – works OK but looks like a shambles



AMS Measurement



RF starts

RF stops

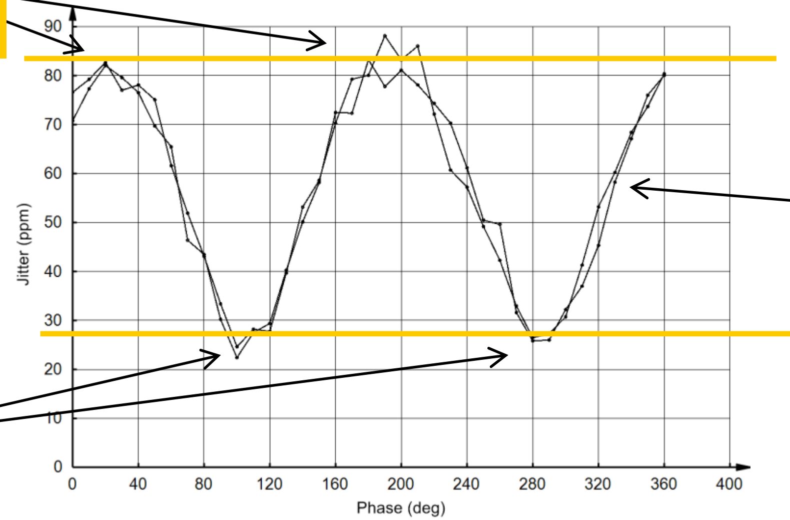
100 consecutive shots at 100Hz, typically 125MS/s, uploaded to computer, analysed for average waveform and deviation from average

RF pulse WOULD be 100 times larger except the interferometer cancels most of the signal

Typically 3us
Could be 300ns – 100us

AMS Result Interpretation

Large SD (large jitter) for +ve and –ve Amplitude Modulation



Each point is scaled Standard Deviation for 100 consecutive shots

Smaller SD (smaller jitter) for +ve and –ve Phase Modulation

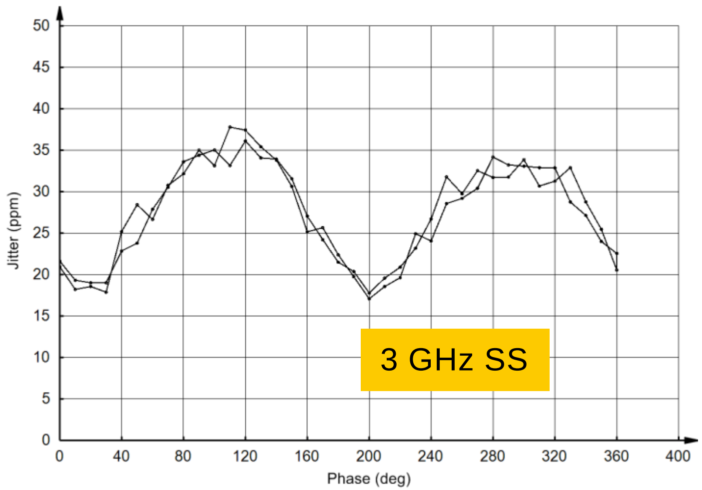
First, the mixer phase is swept in one direction and the SD is recorded, takes about 5 minutes

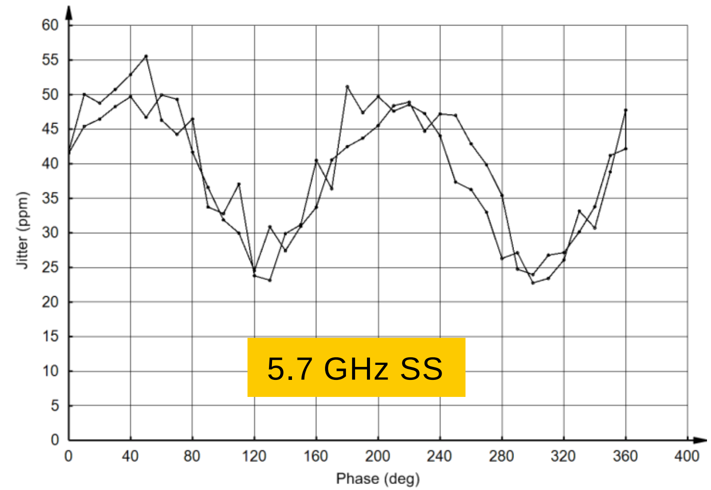
Second, the mixer phase is swept in opposite direction and the SD is recorded, takes about 5 minutes

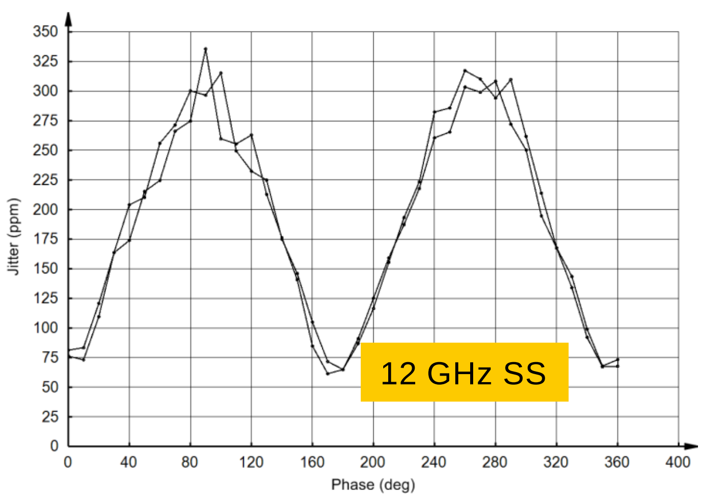
The SD from the mean waveform is given on the vertical axis in parts per million, for example +/-80uV rms vector in phase with a 1.0V sinewave carrier. The same magnitude noise vector rotated 90° with respect to the carrier gives the resulting phase modulation of 80urad. So the vertical scale in ppm / urad is used for both amplitude and phase.

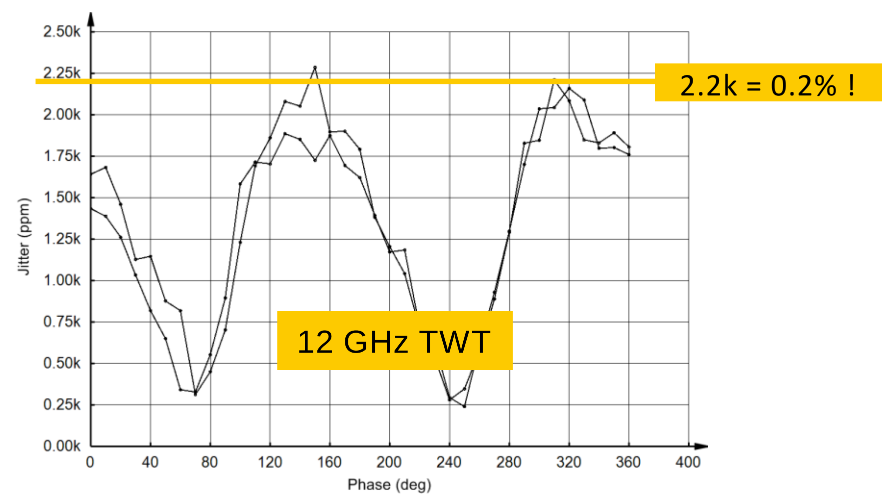
The total measurement time is about ten minutes – this is needed to give some assurance that the measurement is stable and that the amplifier is reasonably free from jitter spikes.

Examples of “Normal” Amplifier Measurements









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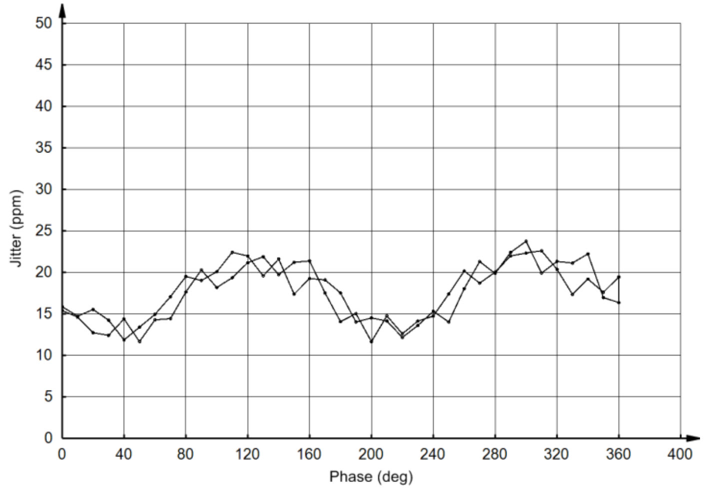
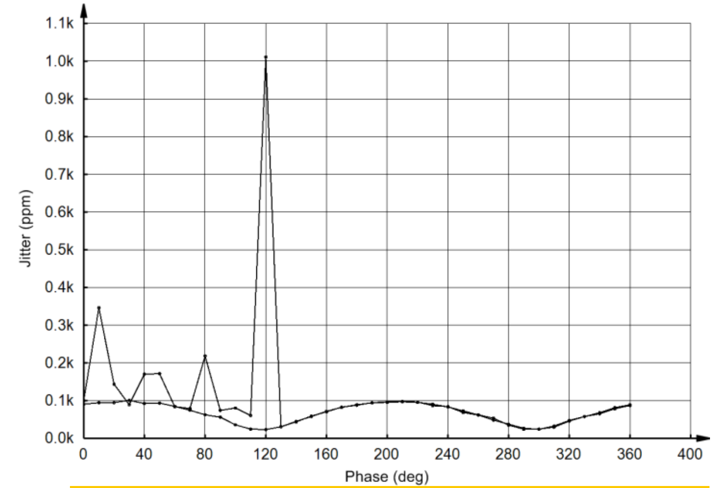
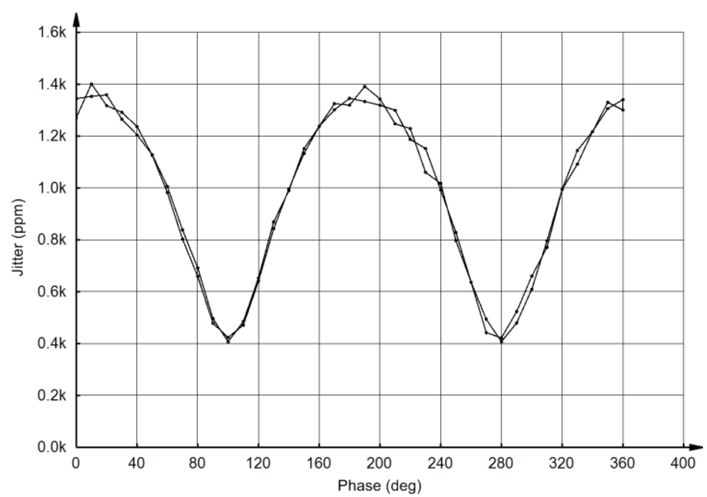
Examples of Amplifier Measurements



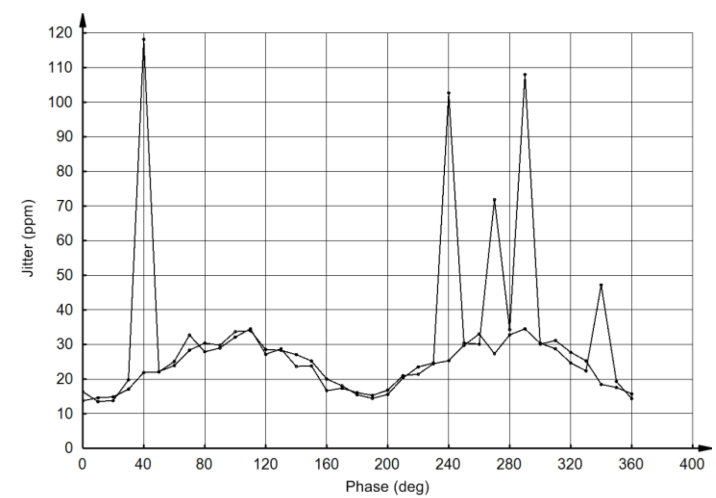
Near thermal noise floor – excellent!
Characteristic: AM and PM about the same level



Slightly loose connector
Characteristic: spikes which change with time

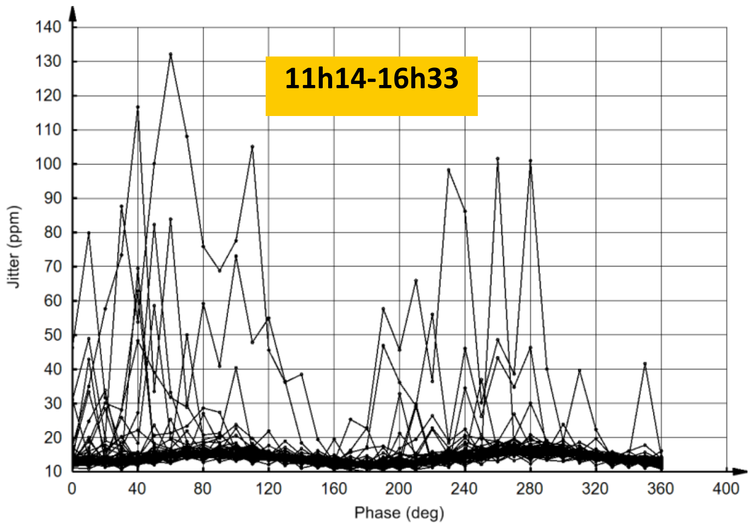


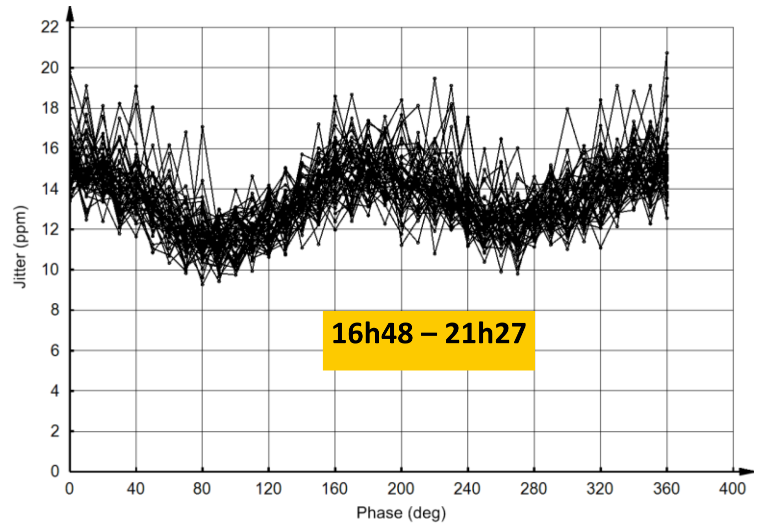
With fan operating
Characteristic: AM and PM stable but too large



Broken contact e.g. ceramic decoupling capacitor
Characteristic: spikes which appear on multiple runs

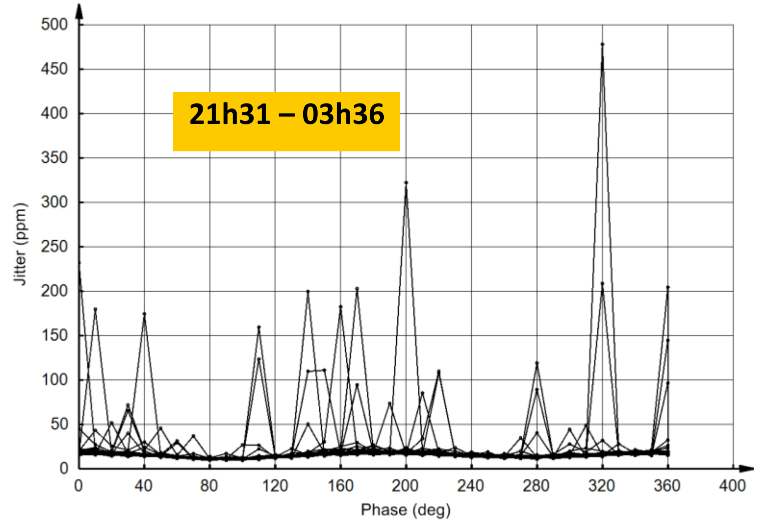
Amplifier Measurement Long Term





Nightmare amplifier!

Continuous operation but erratic contact with no predictability



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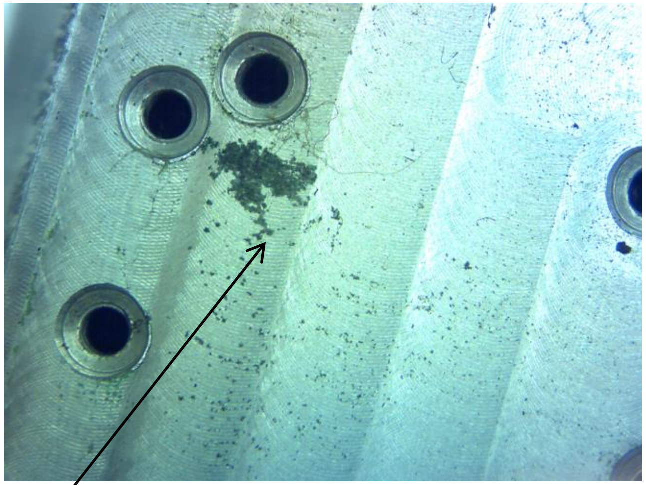
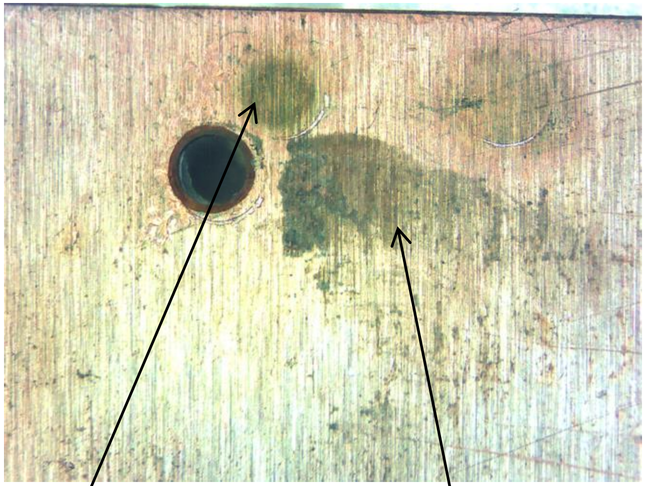
Aluminium – copper clamping





Localised point discharges

Diffuse corona discharges

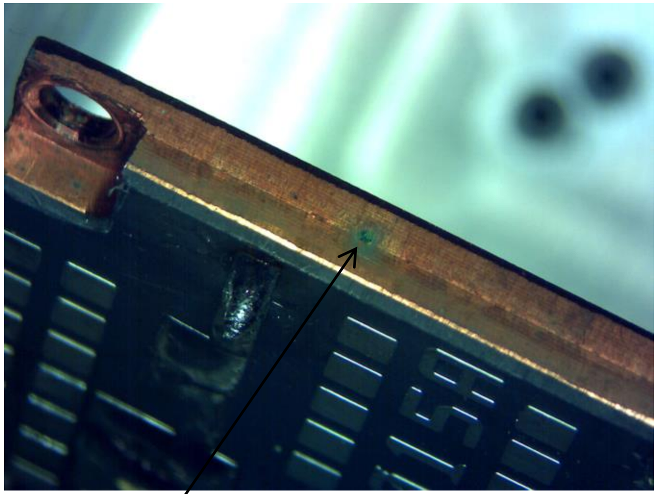
Area discharges

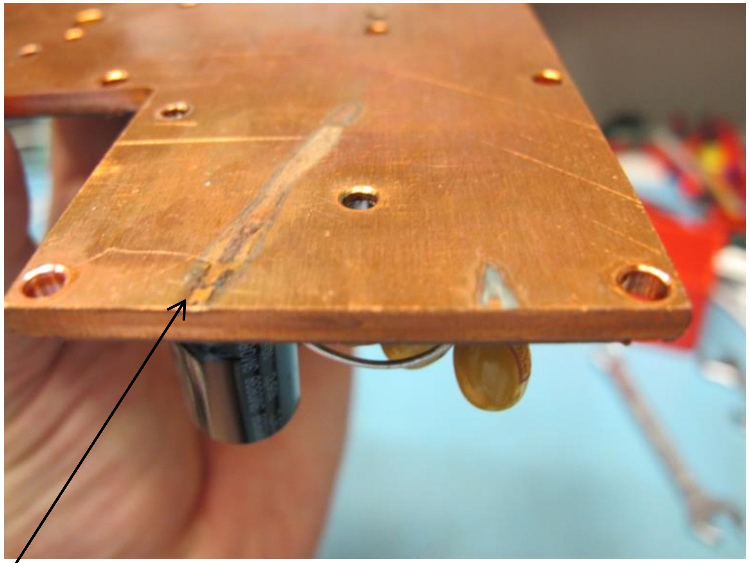
Machined aluminium may be flat but oxide never gives guaranteed contact.

Copper in palettes is annealed and any compression force takes the material beyond yield point – contact under each screw but in between there are always gaps.

The RF discharges shown here may not or may not give jitter.

Aluminium – copper clamping





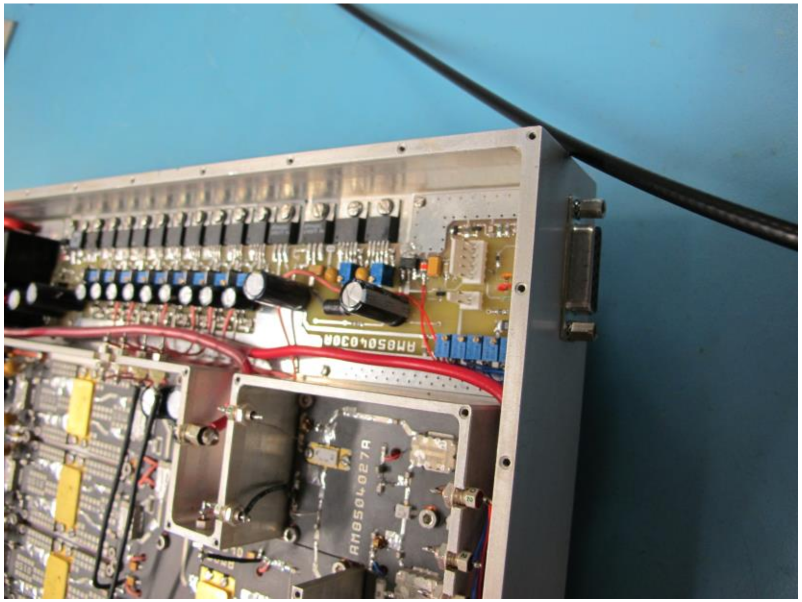
Side of palette touching another palette

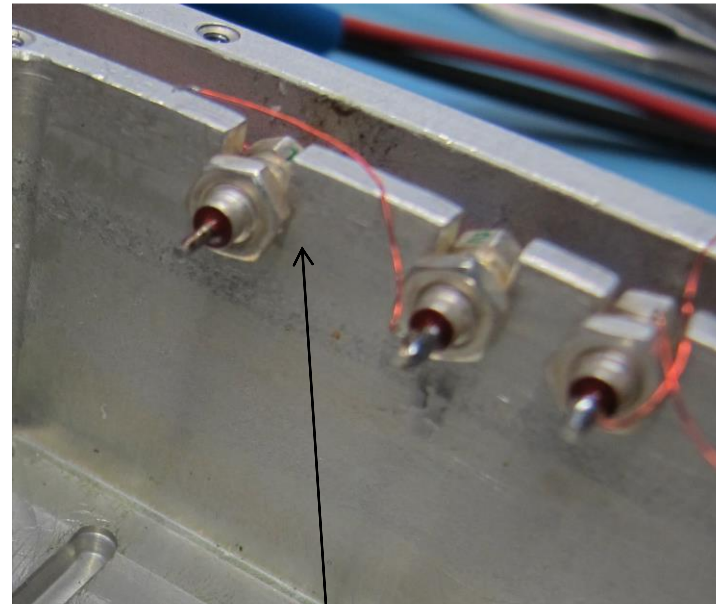
Running discharge

Running discharge

The touching side of the palette gives a jitter problem because transistors can pulse to 50A DC. For microsecond pulses, skin effect means effective resistance is high and changes in path length can easily give millivolt jumps in bias voltage.

Incorrect use of feedthrough capacitors





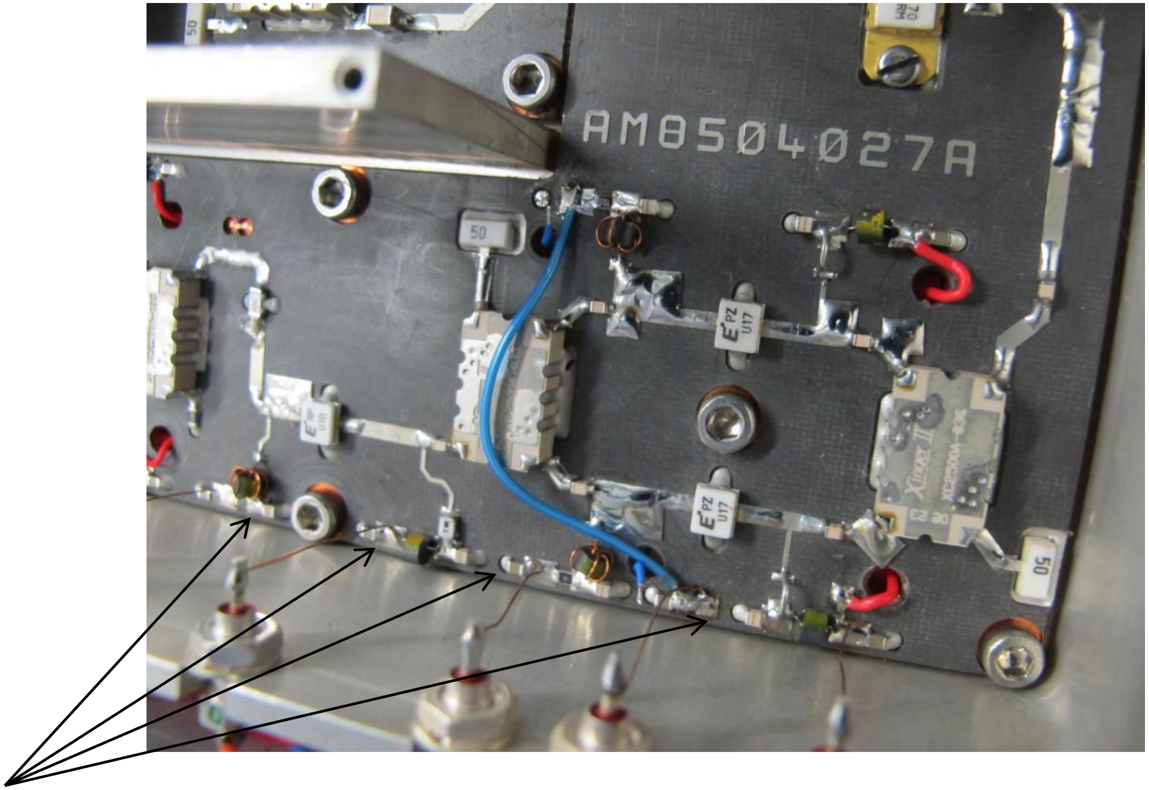
Ceramic feedthroughs

- mounting in slots, high tighening torque needed to hold, feedthrough metal is deformed, consequently about 20% of feedthroughs were broken giving random capacitance between few pF and full value.

- mounting on housing edge where RF contact is uncontrolled

- 10pF is sufficient for RF isolation so use of e.g. 47nF only increases chances of breakage.

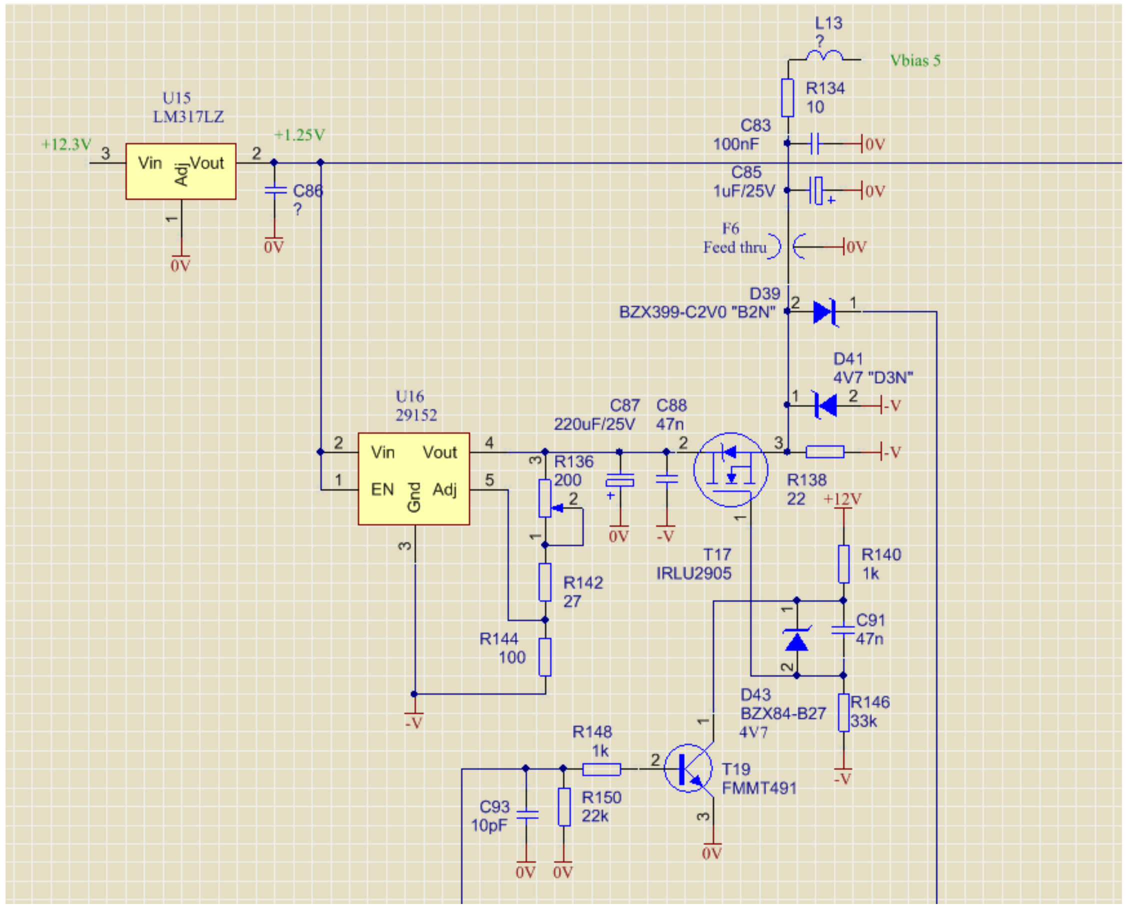
Breaking of ceramic capacitors



Small package 100nF decoupling capacitors stressed by deformation of soft copper baseplate, either on edge or near to screws. Most copper palettes had a few broken capacitors.

Solution: remove EVERY copper palette from aluminium housing, reheat and replace EVERY ceramic capacitor, preferably with a larger 1206 size which seemed to have a stronger package.

Bias voltage with high flicker noise



Bias voltages derived from 78xx type regulators (connection to the RF transistor is upper right marked “Vbias5”). Output filtering is ineffective against flicker noise, which is order of magnitude too high for this application. The regulator quiescent current is near zero.

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Comment on Cable Assemblies

In general, all cables and waveguides give large amplitude and phase change when touched.

This is OK when the cable movement oscillates then phase and amplitude return to the original value. Also OK is when phase and amplitude are drifting in the first few minutes after cables have been shifted – the dielectric is yielding and this gives a ramp which can show up in jitter results. (e.g. 1°/min = 300urad/sec)

What is not OK is when phase and amplitude return to a different value after a transient, indicating a microscopic contact variation.

DC Test for thin coax cables for possible RF jitter

The cable under test is hung from the ceiling, a large DC current through the cable and voltage changes to <1mV are monitored. When jumps are absent, the cable is labelled OK for use in the AMS.

At this level of jitter, this is <u>not</u> a macroscopic intermittent problem which can be identified by hand bending the cable.

Even new cable assemblies can have this behaviour.

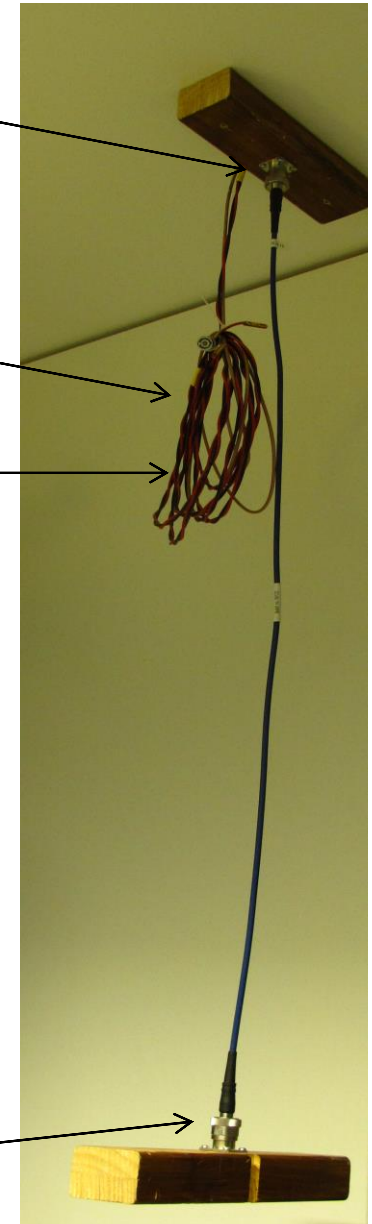
In the AMS, measurements are only possible with all connectors tightened beyond the manufacturers torque value.

N-type connector

Wires to inject 10A DC

Coax to pick off <1mV signals for scope

N-type connector with short circuit



PAUL SCHERRER INSTITUT PSI

AMS used for commercial 500W amplifiers from Advantech (fitted with PSI bias circuit)

Backoff from nominal power

Average Jitter

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1				Amplitude Jitter (ppm)						Phase Jitter (urad)					
2															
3	**PSI Label**	**Barcode**	**Serial**	**0dB**	**-1dB**	**-2dB**	**-3dB**	**-4dB**	**-5dB**	**0dB**	**-1dB**	**-2dB**	**-3dB**	**-4dB**	**-5dB**
4															
23	RFAMP104		AMT-C18418	50	55	55	50	50	50	28	25	25	28	28	28
24	RFAMP105		AMT-C18419	50	50	50	50	55	50	25	25	27	27	30	30
25	RFAMP106		AMT-C17697	50	55	50	53	53	53	33	30	28	25	25	25
26	RFAMP107		AMT-C18417	45	45	50	55	55	50	25	25	25	25	25	25
27	RFAMP108		AMT-C18413	75	75	75	75	75	75	25	25	25	25	25	25
28	RFAMP109		AMT-C18411	70	75	75	75	75	75	28	25	25	25	28	28
29	RFAMP110		AMT-C18414	80	80	80	78	80	80	25	25	25	25	25	25
30	RFAMP111		AMT-C16554	50	45	45	45	50	45	35	35	30	28	24	25
31	RFAMP112		AMT-C18416	65	65	65	65	65	65	28	28	28	28	28	28
32	RFAMP113		AMT-C18415	55	55	50	55	55	50	28	25	25	25	25	25
33	RFAMP114		AMT-C17946	75	75	75	75	75	75	33	33	27	27	27	27
34	RFAMP115		AMT-C17695	65	70	70	70	70	70	30	30	28	25	25	25
35	RFAMP116		AMT-C17699	65	65	65	68	65	65	32	32	32	25	25	23
36	RFAMP117		AMT-C17940	70	70	68	70	70	70	32	32	30	26	26	23
37	RFAMP118		AMT-C17942	55	55	55	55	60	60	35	35	33	28	26	23
38	RFAMP119		AMT-C17944	65	60	65	65	63	63	32	32	28	26	26	28
39	RFAMP120		AMT-C17941	60	60	65	60	60	60	33	30	28	26	25	25
40	RFAMP121		AMT-C17943	65	65	63	65	65	60	35	33	28	25	25	25
41	RFAMP122		AMT-C17945	80	85	85	85	85	85	35	32	28	28	25	25
42	RFAMP123		AMT-C17694	65	62	65	65	64	70	35	30	28	25	23	25
43	RFAMP124		AMT-C17698	69	66	63	70	68	70	35	33	27	28	24	27
44	RFAMP125		AMT-C17947	53	55	55	53	55	56	33	30	27	24	24	26
45	RFAMP126		AMT-C17691	50	55	55	50	50	50	30	29	28	27	26	26
46	RFAMP127		AMT-C17693	50	55	53	55	55	55	33	30	27	27	27	28
47	RFAMP128		AMT-C17692	53	55	55	55	55	55	35	33	27	27	25	24
48	RFAMP129		AMT-C17939	60	55	57	63	62	63	33	27	27	27	27	27
49	RFAMP130		AMT-C17696	56	55	51	55	53	52	34	32	28	27	27	25
50	RFAMP131		AMT-C18412	50	50	47	50	55	48	35	33	28	28	26	27
51	Average			60.571	61.179	60.964	61.786	61.593	61.429	31.429	29.786	27.571	26.321	25.815	25.821
52	StdDev			10.112	10.321	10.609	10.329	9.141	10.816	3.5531	3.3484	1.9707	1.3068	1.5451	1.7438
53	Max			80	85	85	85	85	85	35	35	33	28	30	30
54	Min			45	45	45	45	50	45	25	25	25	24	23	23

Summary for Pulsed Power Amplifiers

- Jitter measurement is only reproducible once the contact problems are cleared out
- All RF material (cables, attenuators, everything) have possible contact problems and must be one-by-one discarded until the measurement is stable.
- Jitter is mainly a low frequency gain variation problem
- Noise on transistor gate bias voltage source must be free from flicker noise to 1uV level
- Noise on transistor drain voltage much less important
- No difference in jitter between pulsed and CW amplifier
- No difference in jitter with RF frequency 3 – 12GHz
- No consistent change in jitter as amplifiers approach saturation
- Probably no difference between GaAs and GaN transistors
- Klystrons tend to clean off amplitude jitter. When amplifiers are used for driving klystrons, tight amplitude jitter specification (<100ppm) for amplifiers is not useful.
- With reasonable commercial design and construction, 60ppm amplitude jitter and 30urad phase jitter are typical. Lower values are possible by using linear power supplies for the entire RF module.

My thanks go to

- Sladjana Dordevic
- Martin Paraliev

References

[0] “*Jitter Measurement to 10ppm Level for Pulsed Power Amplifiers 3-12GHz*”, C.Gough, S.Dordevic, M.Paraliev, THPIK096, IPAC 2017, Copenhagen

[1] “*Residual Phase Noise AM Noise Measurements and Techniques*”, Thomas R. Faulkner and Robert E. Temple, HP Application Note A-116, 2001 (Part No. 03048-90011)

[2] *“Pulsed Carrier Phase Noise Measurements using Agilent E5500 Series Solutions*” PN E5500-1, Jan 2000

[3] *“Advanced interferometric phase and amplitude noise measurements*”, Rubiola E. and Giordano V., Rev.Sci.Instr. Vol 73(6), June 2002, 2445-2457

[4] *“The Measurement of Near-Carrier Noise in Microwave Amplifiers*”, Sann K., IEEE MTT-16(9), September 1968, pp. 761-766

[5] *“Comparison of High Resolution Balanced and Direct Conversion Measurement of SwissFEL Resonant Kicker Amplitude*”, Paraliev M. and Gough C., IEEE Pulsed Power Conference, Austin, USA, May 31 2015-June 4 2015

Definition of Jitter

DEFINITION OF JITTER

In this application, jitter is dominated by random events in the time domain, and the analysis is best done in time domain to identify the causes. During the RF pulse, the interferometer output signal is mixed down to DC then sampled by an oscilloscope to give a single-shot waveform A^n:

$$\boldsymbol{A}_k^n = [a_1^n \dots a_k^n] \quad (1)$$

Typically, N = 100 waveforms, each with K > 300 samples at ~100 Ms/s, are stored. The mean waveform of **A** is:

$$\overline{\boldsymbol{A}_k} = \frac{1}{N}\sum_1^N \boldsymbol{A}_k^n \quad (2)$$

The jitter is defined as the average of the rms deviations from the mean waveform:

$$\sigma = \frac{1}{K}\sum_1^K \sqrt{\frac{1}{N}\sum_1^N (\boldsymbol{A}_k^n - \overline{\boldsymbol{A}_k})^2} \quad (3)$$

Commentary:

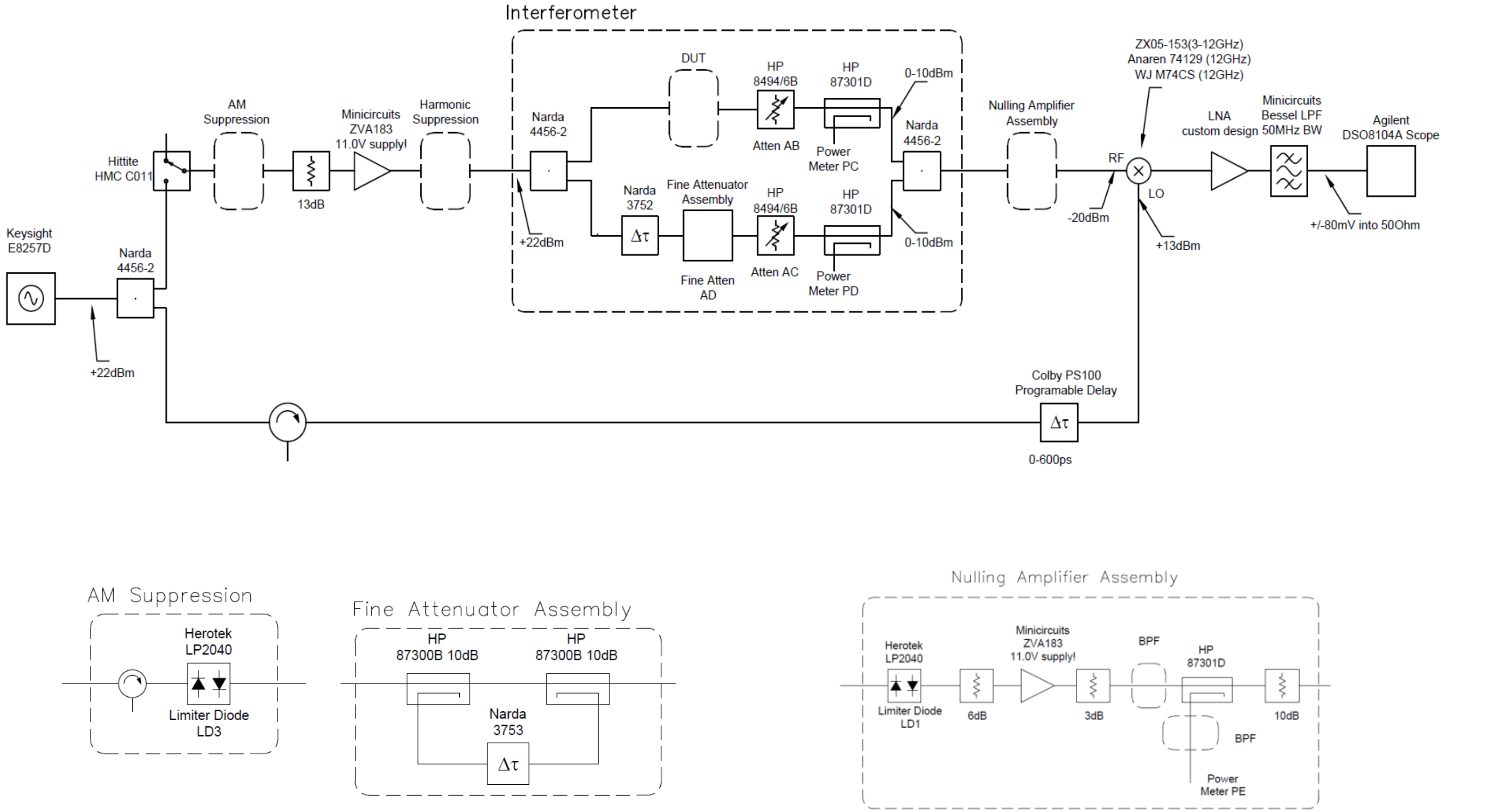
Alternative ideas come when considering the integrating effect of RF accelerating cavities or compression systems.

If there is broadband noise that varies rapidly during a pulse but absolutely no variation from one pulse to the next, then reduction of measured jitter values is possible by changing the definition, for example to:

$$\sigma = \frac{1}{N}\sqrt{\sum_1^N (\overline{\boldsymbol{A}^n} - \overline{\boldsymbol{A}})^2}.$$

If the mean level of the pulse jumps from one pulse to the next, integration during the pulse changes nothing and using the above definition (3) is OK. From measurement, this is the predominant behaviour, put another way, there is flicker noise.

AMS - Amplifier Measurement System Details



Comparison to Phase Noise Measurement

Although some effort was made to find frequency domain solutions, measurements in the time domain were found easier to interpret. Finally, the time domain measurements are also compare well with frequency domain in terms of sensitivity:

The 3us pulse response requires >10MHz measurement bandwidth

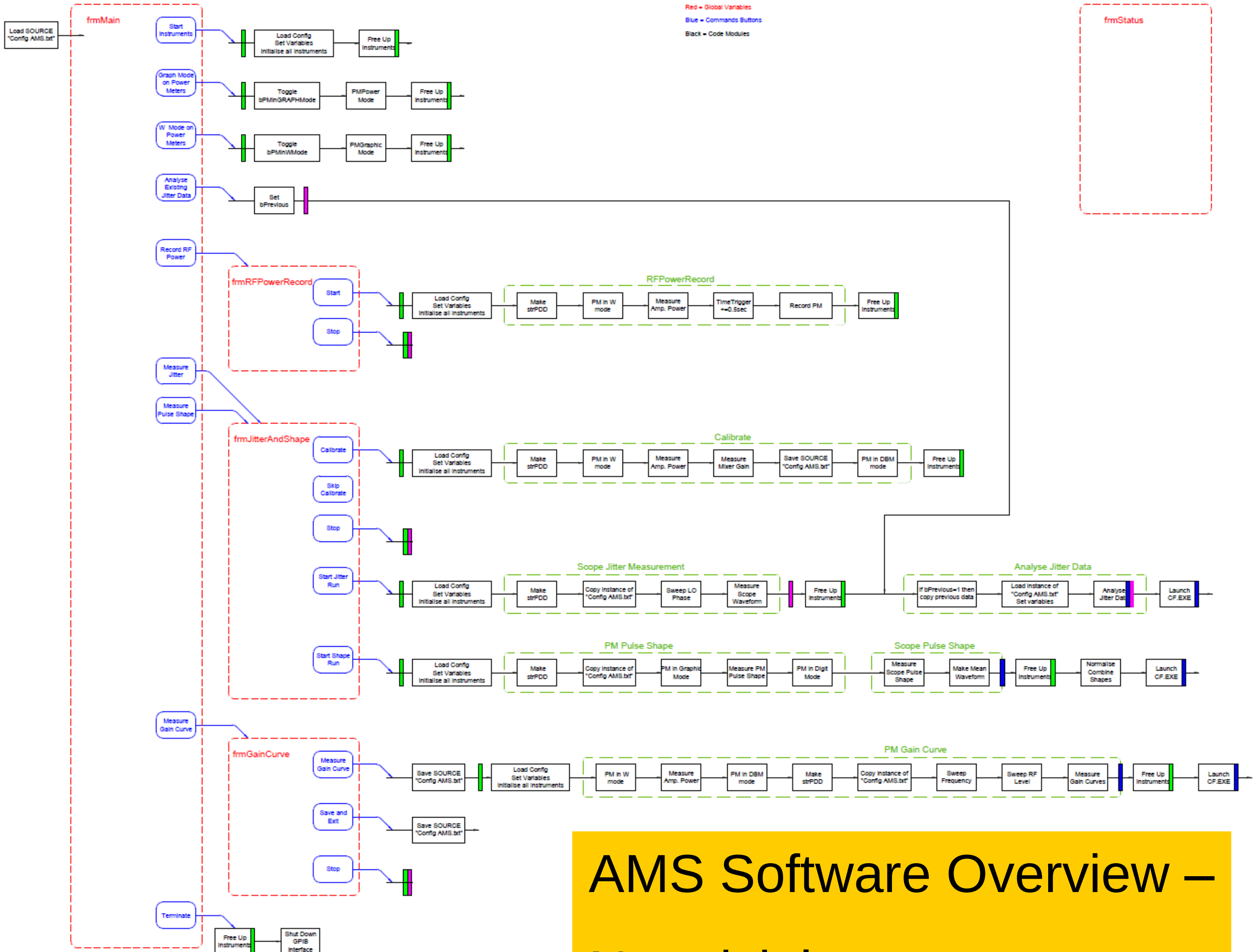
10ppm amplitude corresponds to -100dBc/10MHz,

arguably to -170dBc/Hz !

10 µrad at 12GHz corresponds

arguably to 130as !

Appendix



AMS Software Overview –

Not trivial

These values are taken for stable SASE, user requirements are more relaxed

Table 2.4.4.1: Stability goal assumed to calculate the tolerance budget

Main Beam Parameters for FEL process	Stability Goal at Aramis Entrance	
	200 pC	10 pC
Peak Current Fluctuations (%)	5	15
Beam Arrival Time Jitter (fs)	20	5
Beam Energy Jitter (%)	0.05	

In order to evaluate if those stability goals can be met, we used expected jitter values (Table 2.4.4.2) for all critical accelerator components and multiplied them by the corresponding sensitivities. The final bunch stability (blue bar in Fig. 2.4.4.1) is then the quadratic sum of all independent jitter sources (red bars in Fig. 2.4.4.1) divided by the number of jittering parameters. The obtained electron bunch parameter (peak current; arrival time, energy spread) fluctuations at the undulator entrance are shown in Fig. 2.4.4.1 for the standard 200 pC and 10 pC mode.

These values are rather arbitrary inputs to Bolko's simulation to give a reasonable output

S-Band Phase stability (SBP) [deg]	0.018
S-Band Voltage stability (SBA) [%]	0.018
X-Band Phase stability (XBP) [deg]	0.072
X-Band Voltage stability (XBA) [%]	0.018
Linac 1 Phase stability (L1P) [deg]	0.036
Linac 1 Voltage stability (L1A) [%]	0.018
Linac 2 Phase stability (L2P) [deg]	0.036
Linac 2 Voltage stability (L2A) [%]	0.018
Linac 3 Phase stability (L3P) [deg]	0.036
Linac 3 Voltage stability (L3A) [%]	0.018
Charge stability (LHQ) [pC]	1%
Initial arrival time jitter (LHt) [fs]	30
Initial Energy stability (LHE) [%]	0.01
BC1 angle jitter [%]	0.005
BC2 angle jitter [%]	0.005

Somebody once maybe measured this on one SBand system

All these inputs are copied from the first two

Table 2.4.4.2: Expected RMS stability performance of SwissFEL subsystems. Those tolerances are assumed to simulate the beam performance stability presented in Fig. 2.4.4.1 & Fig. 2.4.4.2.

The assumed tolerances for the S band phase and amplitude stability in Table 2.4.4.2 are obtained from measurements at the SwissFEL Injector Test Facility. The values for the other RF systems are assumed to be a multiples of this.

Appendix CDR Apr 2012

This is the resulting output from the simulation

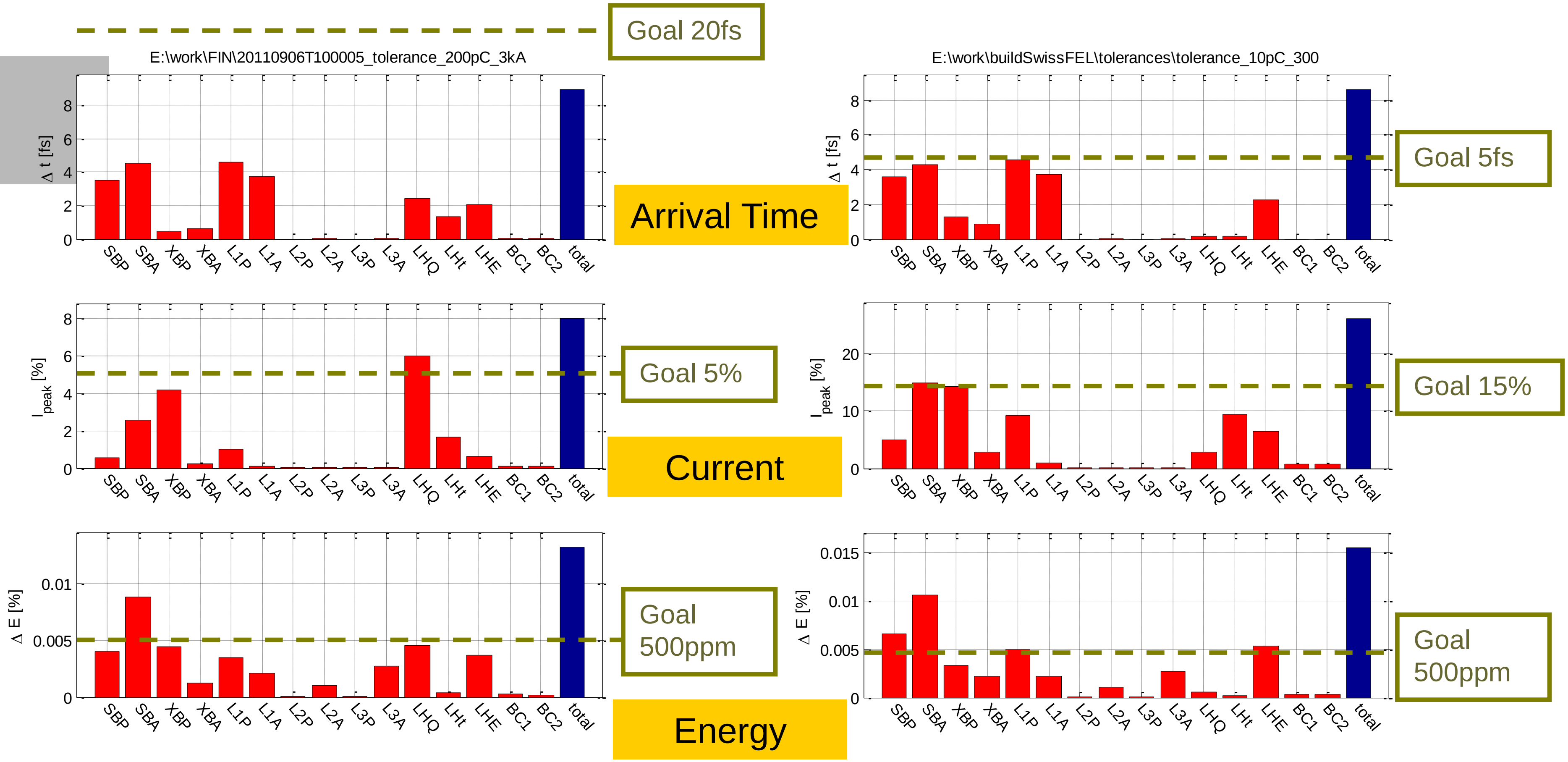


Fig. 2.4.4.1: Expected beam performances of the standard operation modes 10 and 200 pC. The red bars indicate independent RMS jitter sources, their total is given by the blue bar. The arrival time (top), peak current (middle), and energy jitter (bottom) are given for the 200 pC (left) and 10 pC mode (right). The jitter denomination (SBP; SBA ...) is explained in Table 2.4.4.2.