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

LLRF Workshop, Barcelona, 16-19 October 2017
Introduction

Amplifier Measurement System and Typical Results

Examples of Poor Amplifier Design

Summary for Amplifier Users
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

Two Main Causes of Power Amplifier Jitter

1. Erratic RF contact

2. Flicker noise in gate bias of RF transistors

The RF levels are high, the signal of interest is narrow band so **additive** thermal noise at RF is not the main concern. Jitter in this application is caused by gain changes, that is **multiplicative**.

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

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
Each point is scaled Standard Deviation for 100 consecutive shots

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

3 GHz SS

5.7 GHz SS

12 GHz SS

12 GHz TWT

2.2k = 0.2% !
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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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.
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 tightening 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 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 noise is maximised because 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 not 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.
AMS used for commercial 500W amplifiers from Advantech (fitted with PSI bias circuit)

#### Table: Amplitude Jitter (ppm) and Phase Jitter (urad)

| PSI Label | Barcode   | Serial | 0dB | -1dB | -2dB | -3dB | -4dB | -5dB | 0dB | -1dB | -2dB | -3dB | -4dB | -5dB |
|-----------|-----------|--------|-----|------|------|------|------|------|-----|------|------|------|------|------|------|
| RFAMP104  | AMT-C18418| 50     | 55  | 55   | 50   | 50   | 50   | 28   | 25  | 25   | 25   | 25   | 28   | 28   | 28   |
| RFAMP105  | AMT-C18419| 50     | 50   | 50   | 50   | 50   | 50   | 25   | 25  | 27   | 27   | 27   | 30   | 30   | 30   |
| RFAMP106  | AMT-C17697| 50     | 55   | 50   | 50   | 53   | 53   | 53   | 33  | 30   | 28   | 25   | 25   | 25   | 25   |
| RFAMP107  | AMT-C18417| 45     | 45   | 50   | 50   | 55   | 55   | 50   | 25  | 25   | 25   | 25   | 25   | 25   | 25   |
| RFAMP108  | AMT-C18413| 75     | 75   | 75   | 75   | 75   | 75   | 25   | 25  | 25   | 25   | 25   | 25   | 25   | 25   |
| RFAMP109  | AMT-C18411| 70     | 75   | 75   | 75   | 75   | 75   | 28   | 25  | 25   | 25   | 28   | 28   | 28   | 28   |
| RFAMP110  | AMT-C18414| 80     | 80   | 80   | 78   | 80   | 80   | 25   | 25  | 25   | 25   | 25   | 25   | 25   | 25   |
| RFAMP111  | AMT-C16554| 50     | 45   | 45   | 45   | 50   | 45   | 35   | 35  | 30   | 28   | 24   | 25   | 25   | 25   |
| RFAMP112  | AMT-C18416| 65     | 65   | 65   | 65   | 65   | 65   | 28   | 28  | 28   | 28   | 28   | 28   | 28   | 28   |
| RFAMP114  | AMT-C17946| 75     | 75   | 75   | 75   | 75   | 75   | 33   | 33  | 27   | 27   | 27   | 27   | 27   | 27   |
| RFAMP115  | AMT-C17695| 65     | 70   | 70   | 70   | 70   | 70   | 30   | 30  | 28   | 25   | 25   | 25   | 25   | 25   |
| RFAMP116  | AMT-C17699| 65     | 65   | 65   | 68   | 65   | 65   | 32   | 32  | 32   | 25   | 25   | 25   | 25   | 25   |
| RFAMP117  | AMT-C17940| 70     | 70   | 68   | 70   | 70   | 70   | 32   | 32  | 30   | 26   | 26   | 26   | 26   | 26   |
| RFAMP118  | AMT-C17942| 55     | 55   | 55   | 55   | 60   | 60   | 35   | 35  | 35   | 33   | 28   | 26   | 26   | 26   |
| RFAMP119  | AMT-C17944| 65     | 60   | 65   | 65   | 63   | 63   | 32   | 32  | 28   | 26   | 26   | 26   | 26   | 26   |
| RFAMP120  | AMT-C17941| 60     | 60   | 65   | 60   | 60   | 60   | 33   | 30  | 28   | 26   | 25   | 25   | 25   | 25   |
| RFAMP121  | AMT-C17943| 65     | 65   | 63   | 65   | 65   | 60   | 35   | 33  | 28   | 25   | 25   | 25   | 25   | 25   |
| RFAMP122  | AMT-C17945| 80     | 85   | 85   | 85   | 85   | 85   | 35   | 32  | 28   | 25   | 25   | 25   | 25   | 25   |
| RFAMP123  | AMT-C17694| 65     | 62   | 66   | 65   | 64   | 70   | 35   | 30  | 28   | 25   | 23   | 25   | 25   | 25   |
| RFAMP124  | AMT-C17698| 69     | 66   | 63   | 70   | 68   | 70   | 35   | 33  | 27   | 28   | 24   | 27   | 24   | 27   |
| RFAMP125  | AMT-C17947| 53     | 55   | 55   | 55   | 55   | 55   | 33   | 30  | 27   | 24   | 26   | 24   | 26   | 24   |
| RFAMP126  | AMT-C17691| 50     | 55   | 55   | 50   | 50   | 50   | 30   | 29  | 28   | 27   | 26   | 26   | 26   | 26   |
| RFAMP127  | AMT-C17693| 50     | 55   | 53   | 55   | 55   | 55   | 33   | 30  | 27   | 27   | 27   | 27   | 27   | 27   |
| RFAMP128  | AMT-C17692| 53     | 55   | 55   | 55   | 55   | 55   | 35   | 33  | 27   | 27   | 27   | 27   | 27   | 27   |
| RFAMP129  | AMT-C17939| 60     | 55   | 57   | 63   | 62   | 63   | 33   | 27  | 27   | 27   | 27   | 27   | 27   | 27   |
| RFAMP130  | AMT-C17696| 56     | 55   | 51   | 55   | 53   | 52   | 34   | 32  | 28   | 27   | 27   | 27   | 27   | 27   |
| RFAMP131  | AMT-C18412| 50     | 50   | 47   | 50   | 55   | 48   | 35   | 33  | 28   | 26   | 26   | 26   | 26   | 26   |

| Average  | 60.571 | 61.179 | 60.964 | 61.786 | 61.593 | 61.429 | 61.429 | 29.786 | 27.571 | 26.321 | 25.815 | 25.821 |
| Max      | 80     | 85     | 85     | 85     | 85     | 85     | 35     | 35     | 33     | 30     | 30      | 30      |
| 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
[0] “Jitter Measurement to 10ppm Level for Pulsed Power Amplifiers 3-12GHz”, C. Gough, S. Dordevic, M. Paraliev, THPIK096, IPAC 2017, Copenhagen


**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 $A^n$:

$$A_k^n = [a_1^n \ldots a_k^n]$$  \hspace{1cm} (1)

Typically, $N = 100$ waveforms, each with $K > 300$ samples at $\sim 100 \text{ Ms/s}$, are stored. The mean waveform of $A$ is:

$$\overline{A}_k = \frac{1}{N} \sum_1^N A_k^n$$  \hspace{1cm} (2)

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

$$\sigma = \frac{1}{K} \sum_1^K \sqrt{\frac{1}{N} \sum_1^N (A_k^n - \overline{A}_k)^2}$$  \hspace{1cm} (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:

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

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.
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!
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

<table>
<thead>
<tr>
<th>Main Beam Parameters for FEL process</th>
<th>Stability Goal at Aramis Entrance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200 pC</td>
</tr>
<tr>
<td>Peak Current Fluctuations (%)</td>
<td>5</td>
</tr>
<tr>
<td>Beam Arrival Time Jitter (fs)</td>
<td>20</td>
</tr>
<tr>
<td>Beam Energy Jitter (%)</td>
<td></td>
</tr>
</tbody>
</table>

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.
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.

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

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

Somebody once maybe measured this on one S Band system.

All these inputs are copied from the first two.
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.