Implementation of the On-line RF Amplitude and Phase Calibration for Vector Sum Control.

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Institute for Basic Science

Agenda

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- RF power and control

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- Principle of operation

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05 Results

- Limitations

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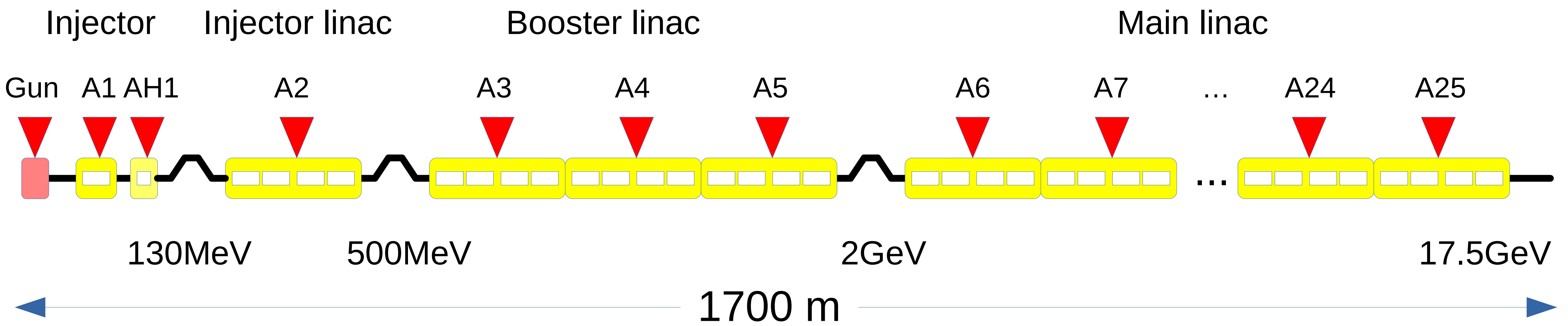
- On-crest measurements

07 Conclusion

XFEL linac



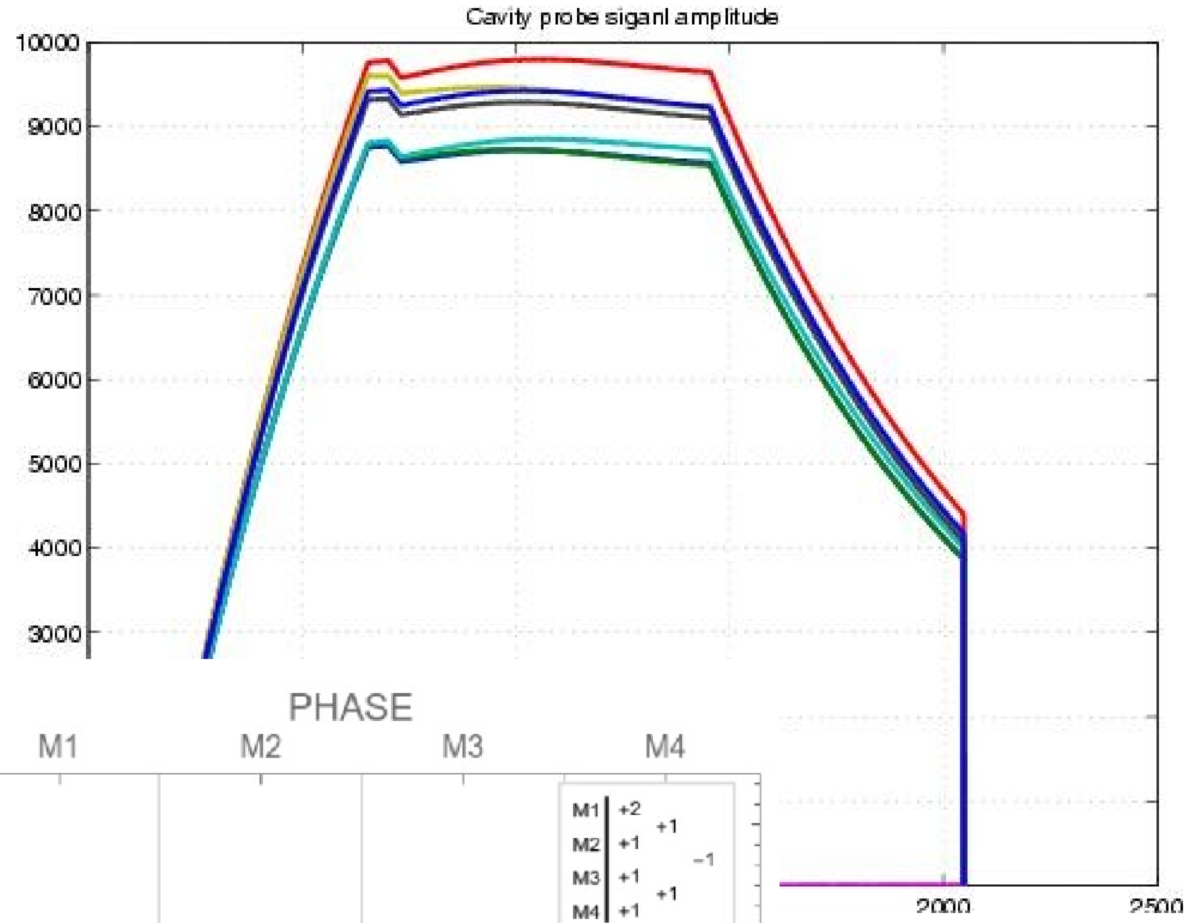
- RF Gun
- 2 RF stations with 8 cavities
- 24 RF stations with 1.3GHz 32 TESLA type cavity each
- in total 784 cavities and 26 RF sources (only SC cavities)

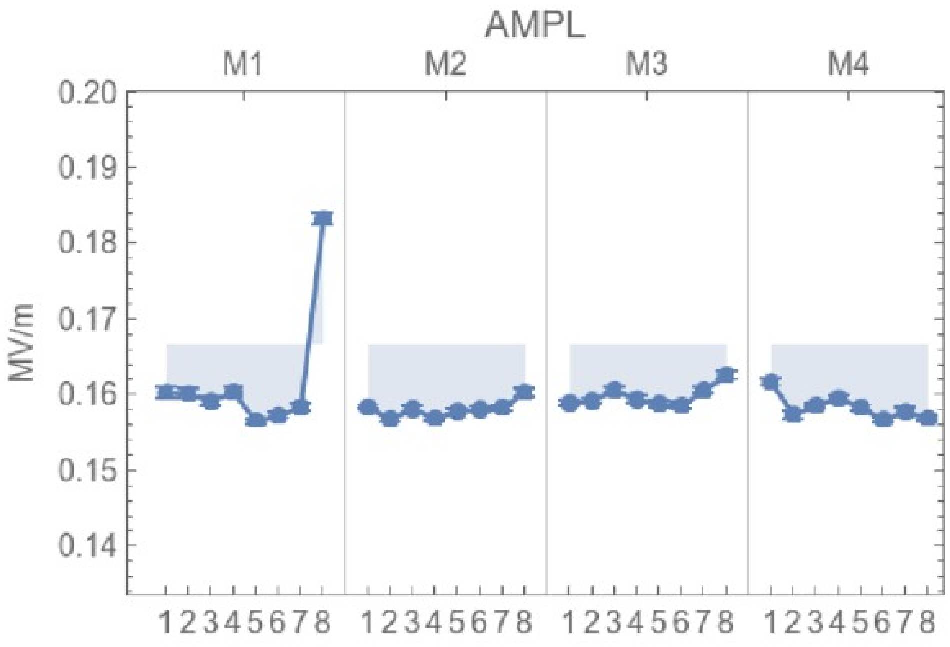
- VS regulation (beem calibration needed)
- XFEL requirements for field stability: 0.01% for amplitude and 0.01 deg. for phase

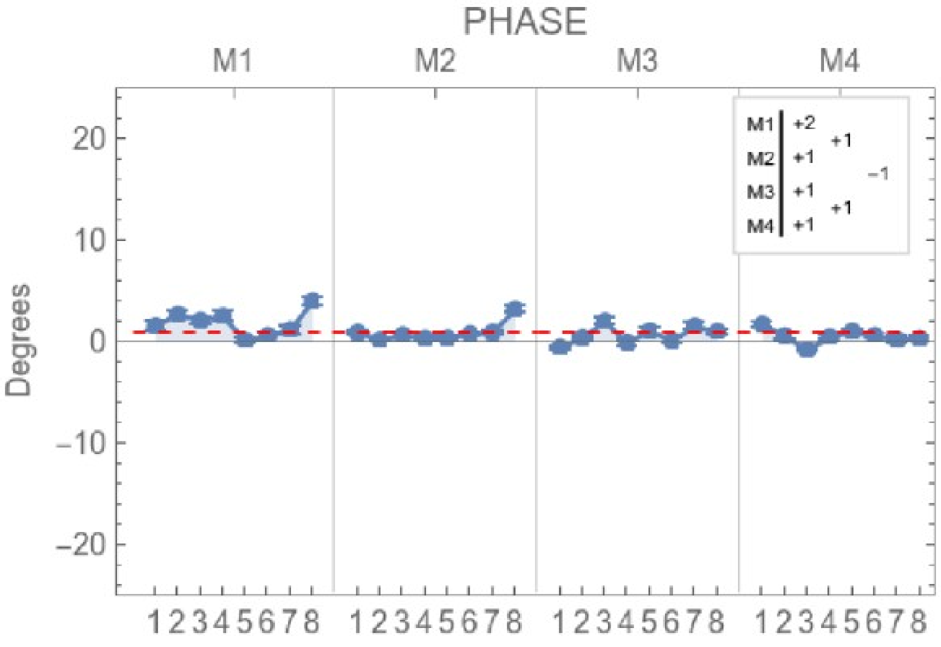
Traditional VS calibration

Standard method at XFE (requires interruption of the normal operation)

- Run station in FF only mode
- Allow short bunch train beam (usually we use up to 200 bunches, more charge is better)
- Record and analyze probe transients caused to beam
- Document results in a report form







Implemented algorithm

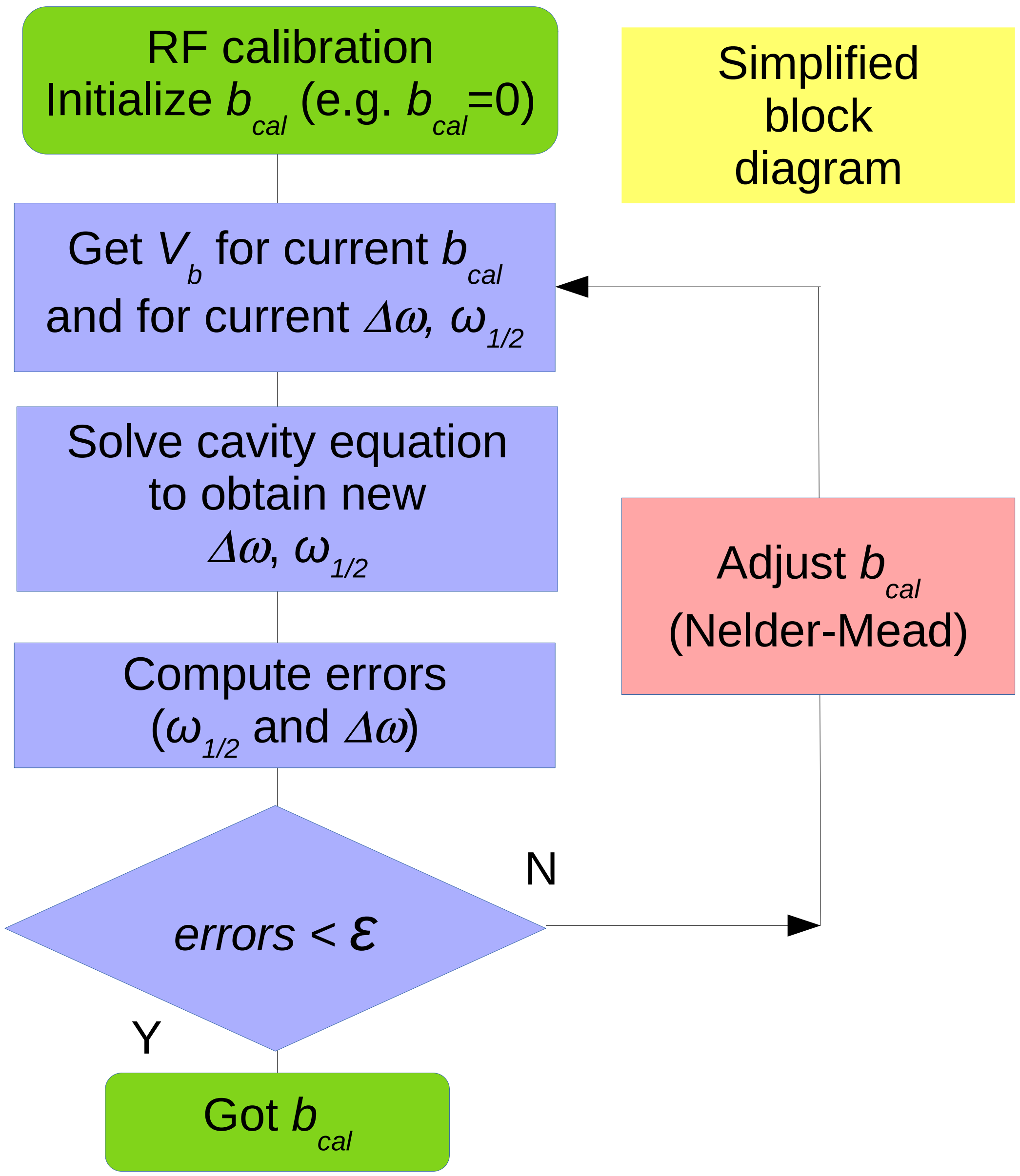
The goal is to obtain b_{cal} - complex factor scaling the beam induced voltage in the cavity equation

$$b_{cal} = k_b e^{j\varphi_b} \Rightarrow V_b^\delta = b_{cal} * 2\omega_{1/2} q R_L$$

$$\frac{dV_c}{dt} = -(\omega_{1/2} - i\Delta\omega) V_c + \omega_{1/2}(2V_f + 2V_b)$$

$\omega_{1/2}$ – halfbandwidth $\Delta\omega$ - detuning
V_c – cavity voltage V_f – forward voltage
V_b – beam induced voltage

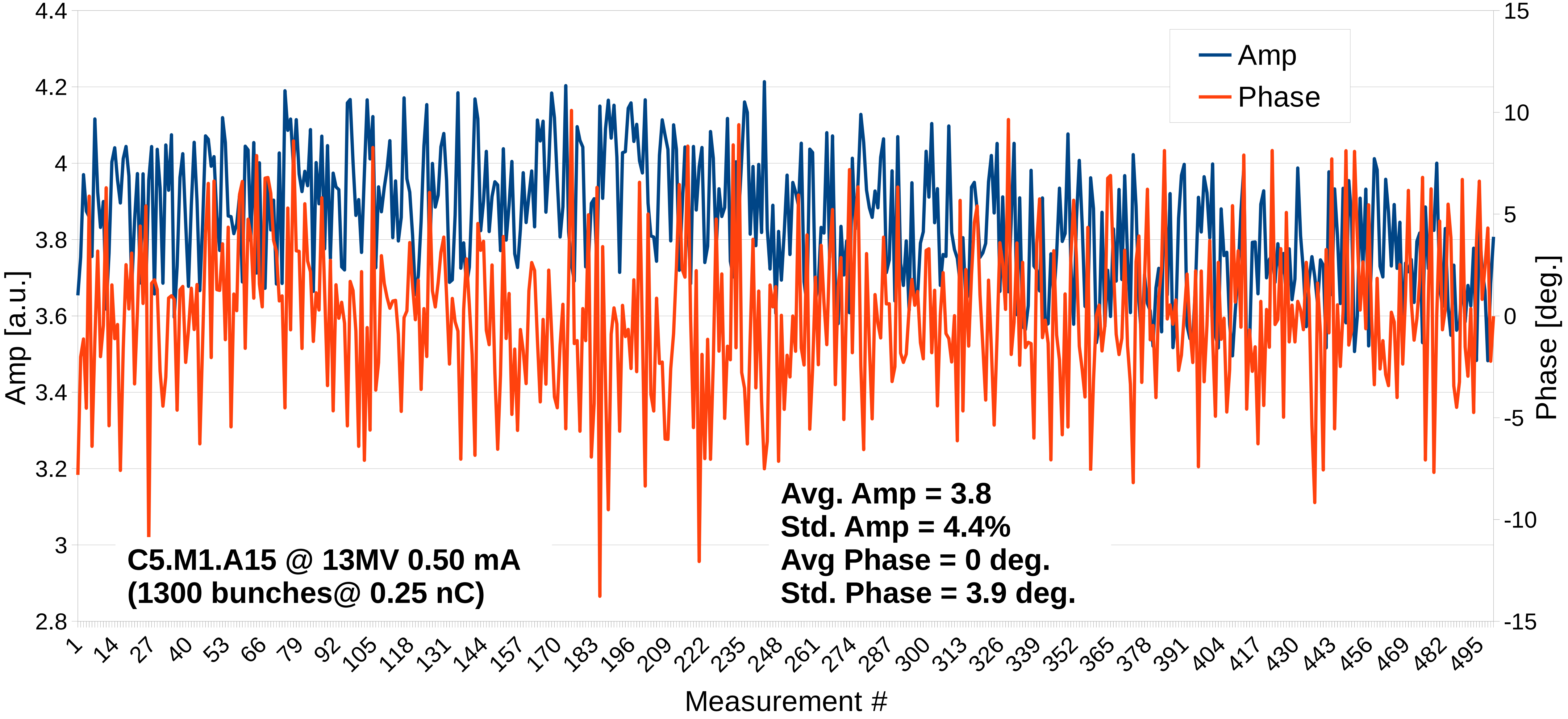
- The beam induced voltage component V_b is a series of steps corresponding to the individual charge bunches, V_b^δ (response to single bunch) as a voltage step (φ_b is a beam phase)
- Relies on iterative signal fitting and error minimization



Software architecture and functionality

- LLRF application (Python), uses DOOCS Api (pydoocs) for communication with LLRF server
- Uses standard scientific python libraries (numpy, scipy) and C++ compiled functions to boost the performance (ctype library)
- Uses multiprocessing for parallel computation, process communication through pipes and shared memory
- Command line application, no GUI
  - GUI can be connected as an external application communicating through pipes and shared memory
- Running on Fujitsu server (72 processing cores, 64GB RAM memory)
- Processing data from single RF station at a time
  - Taking data from LLRF controller for all 32 cavities simultaneously
  - Processing (due to hardware limitations must be serialized, maximum 5 cavities at the moment)
  - Store output (computed beam calibration)
  - Computes the on-crest phase for the module base on the beam calibration for all cavities and store the output

Results

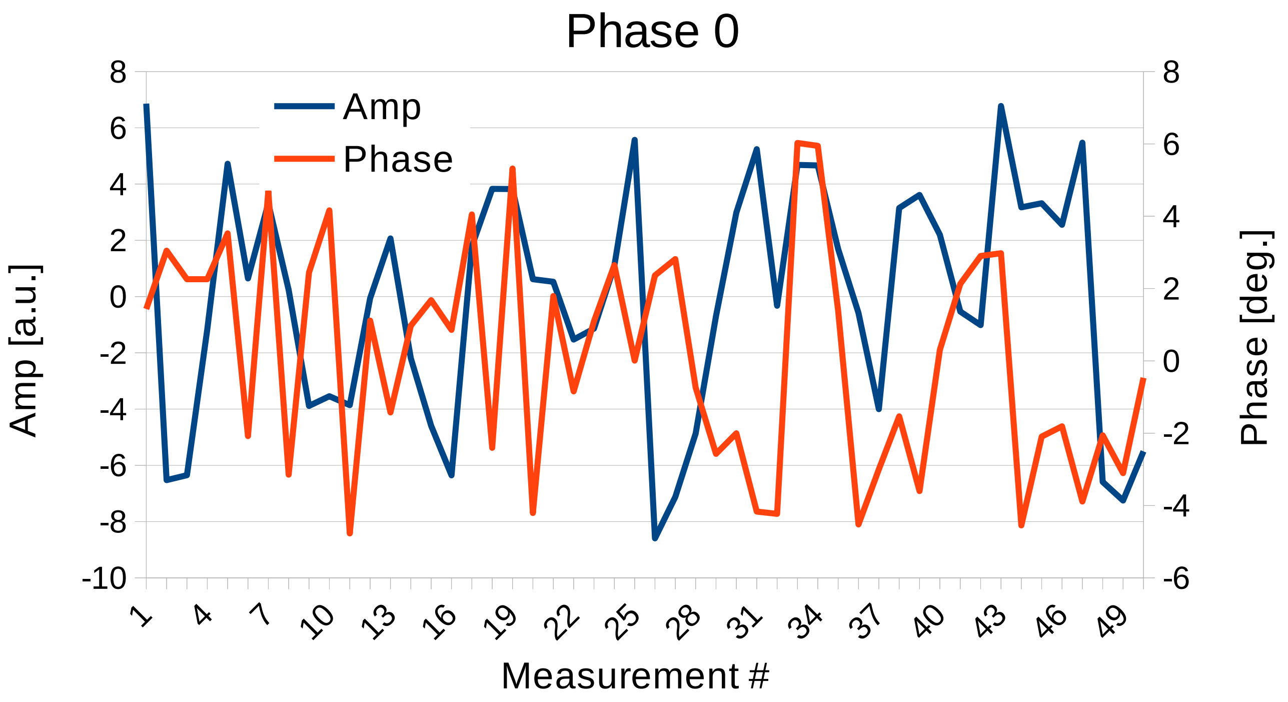


Amp
Phase
Avg. Amp = 3.8
Std. Amp = 4.4%
Avg Phase = 0 deg.
Std. Phase = 3.9 deg.
C5.M1.A15 @ 13MV 0.50 mA
(1300 bunches@ 0.25 nC)
Amp [a.u.]
Phase [deg.]
Measurement #
4.4
4.2
4
3.8
3.6
3.4
3.2
3
2.8
15
10
5
0
-5
-10
-15
1
14
27
40
53
66
79
92
105
118
131
144
157
170
183
196
209
222
235
248
261
274
287
300
313
326
339
352
365
378
391
404
417
430
443
456
469
482
495

Results

As a proof of principle we have measured the beam calibration in one cavity while intentionally have changed the control system calibration settings (only in narrow range and only in one of 32 cavities, so the impact for machine operation was negligible).

- Calibration of the C5.M1.A15.L3 was changed in amplitude and in phase. The scan range was ±20 deg. in phase and ±4% in amplitude respectively.
- For each scan point 500 pulses were recorded and processed after averaging every group of 10 pulses, in total giving 50 measurements for each scan point



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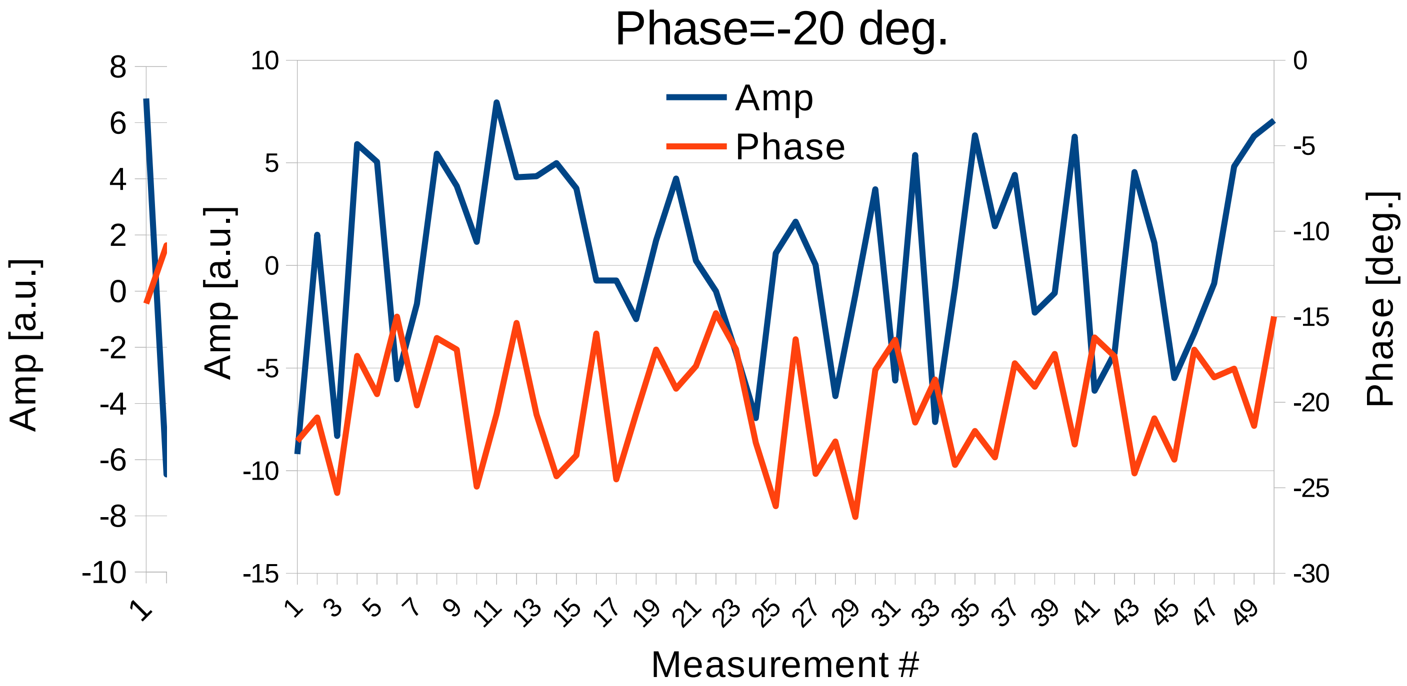

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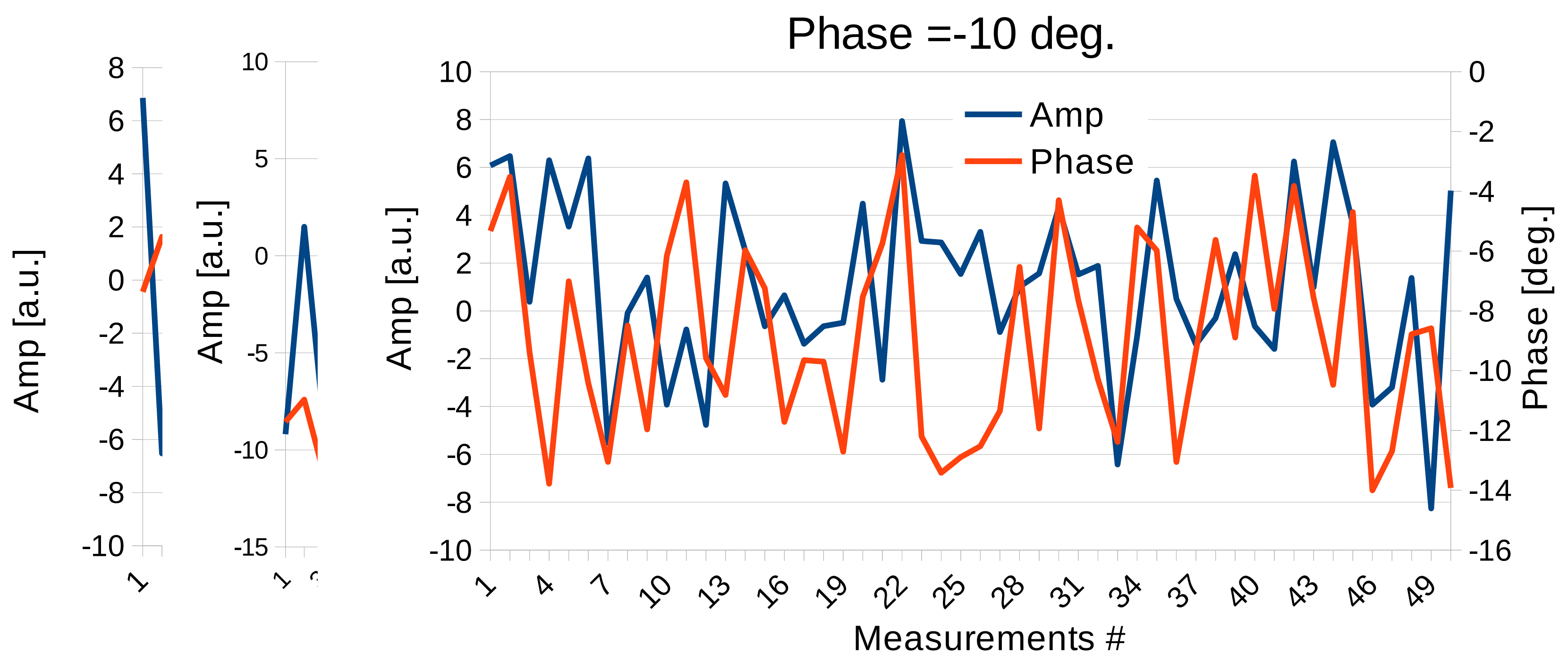

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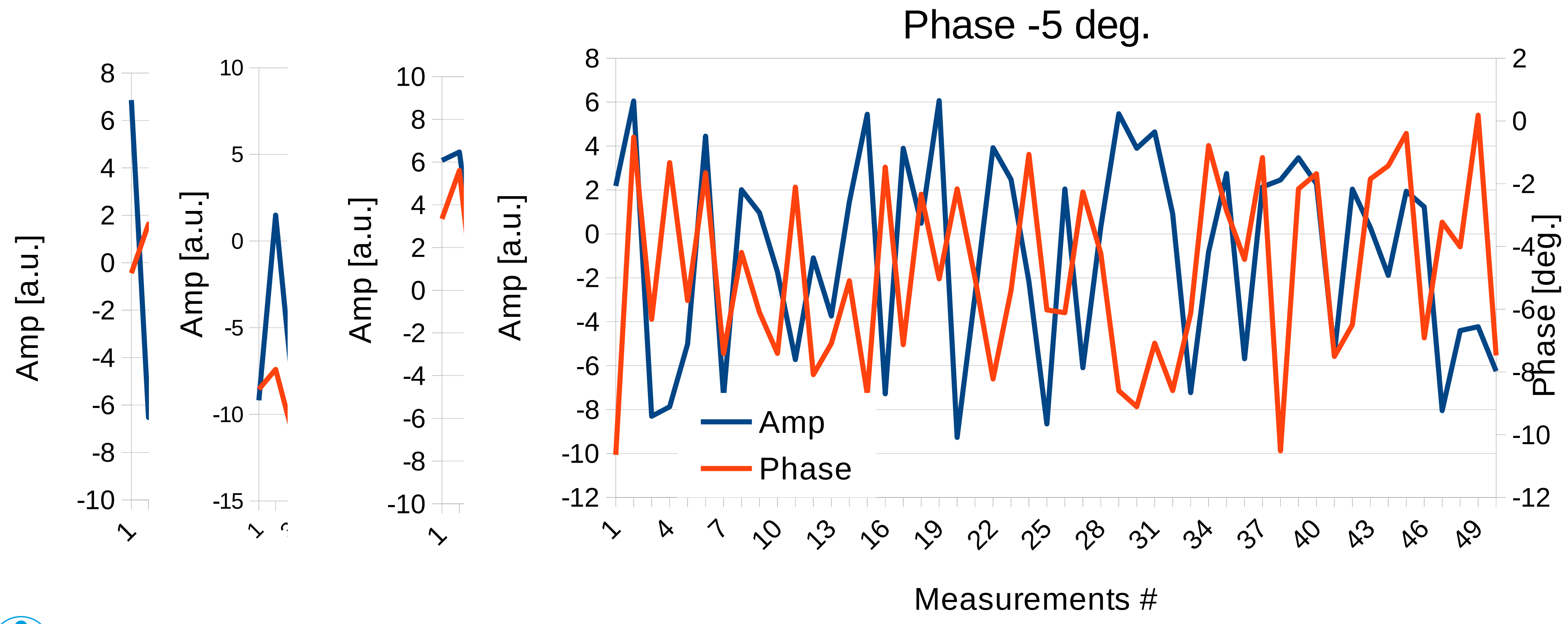

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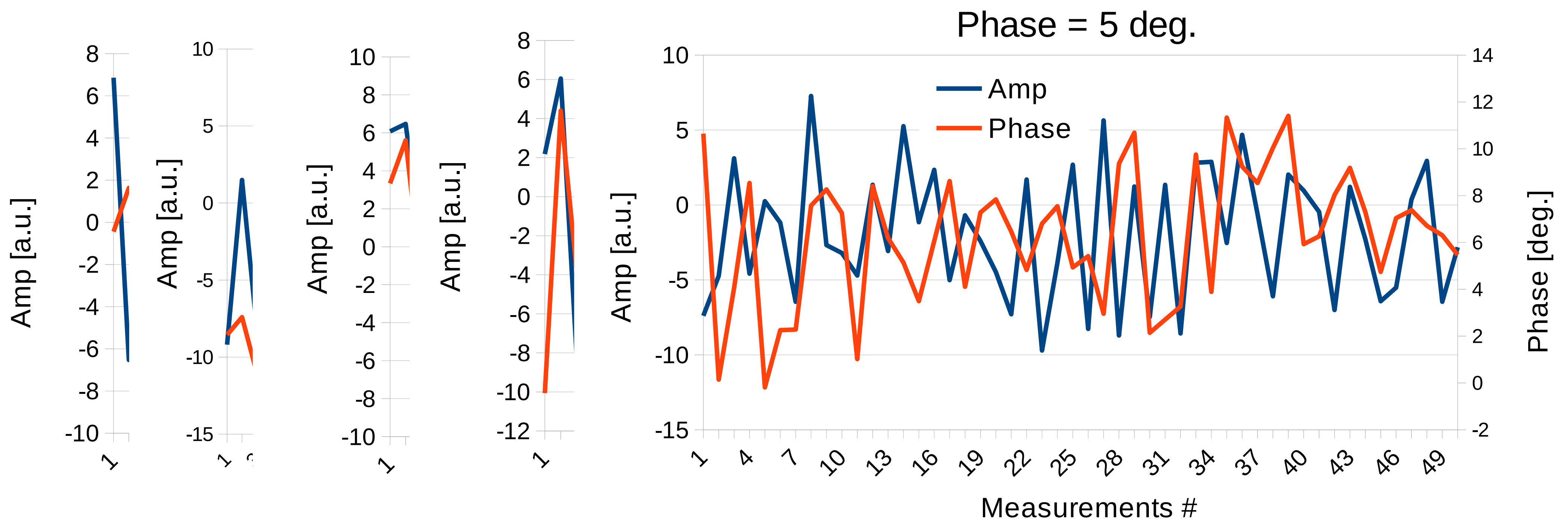

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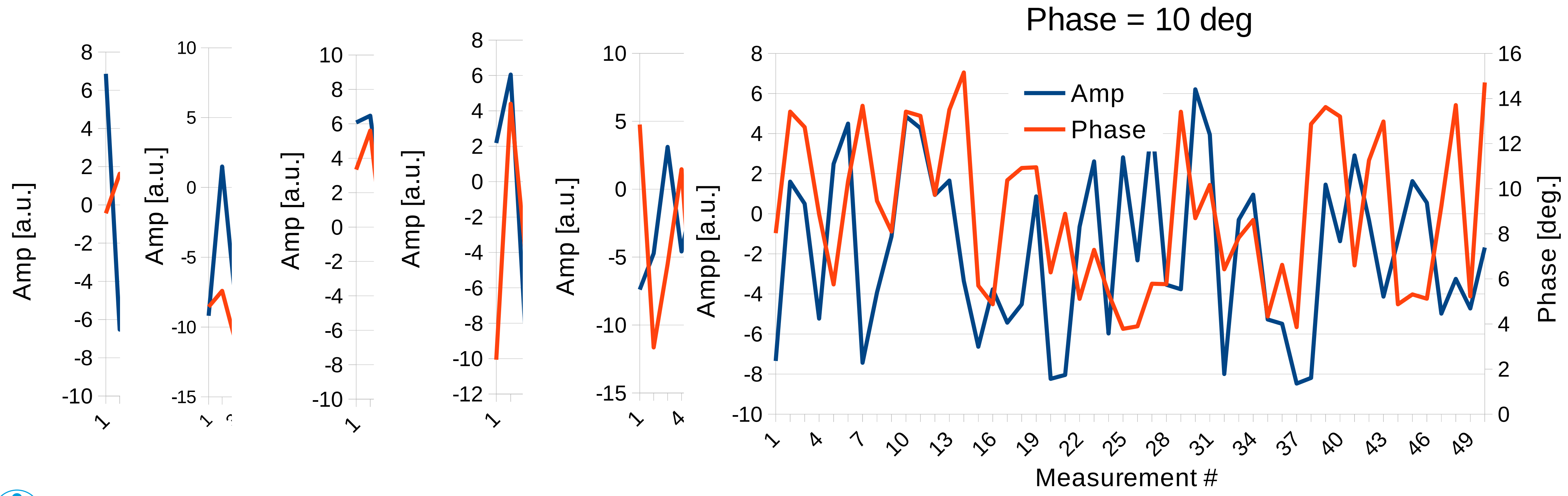

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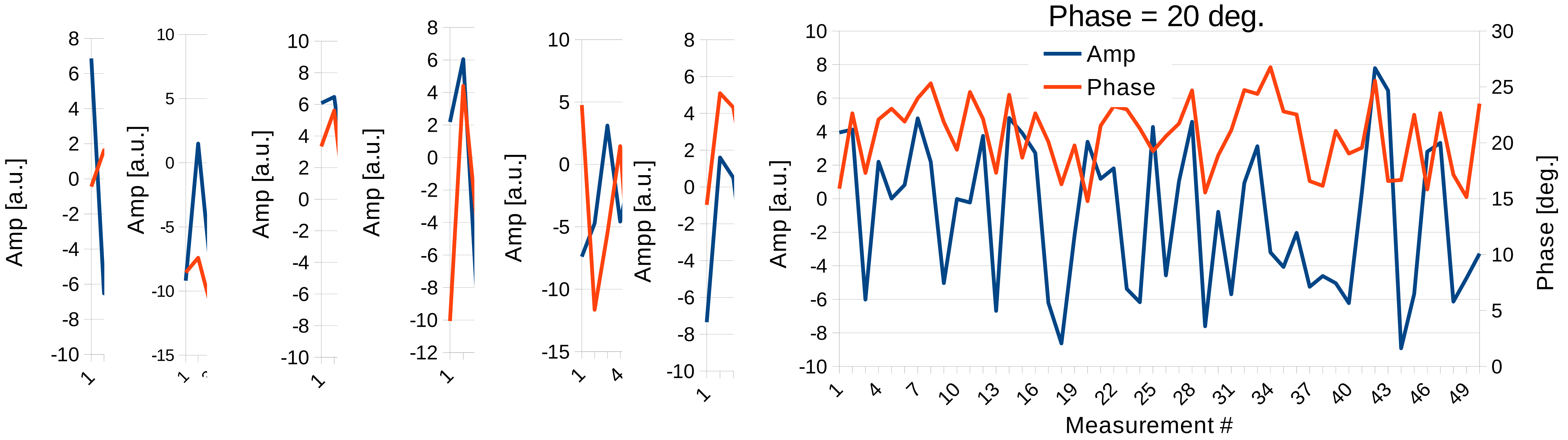

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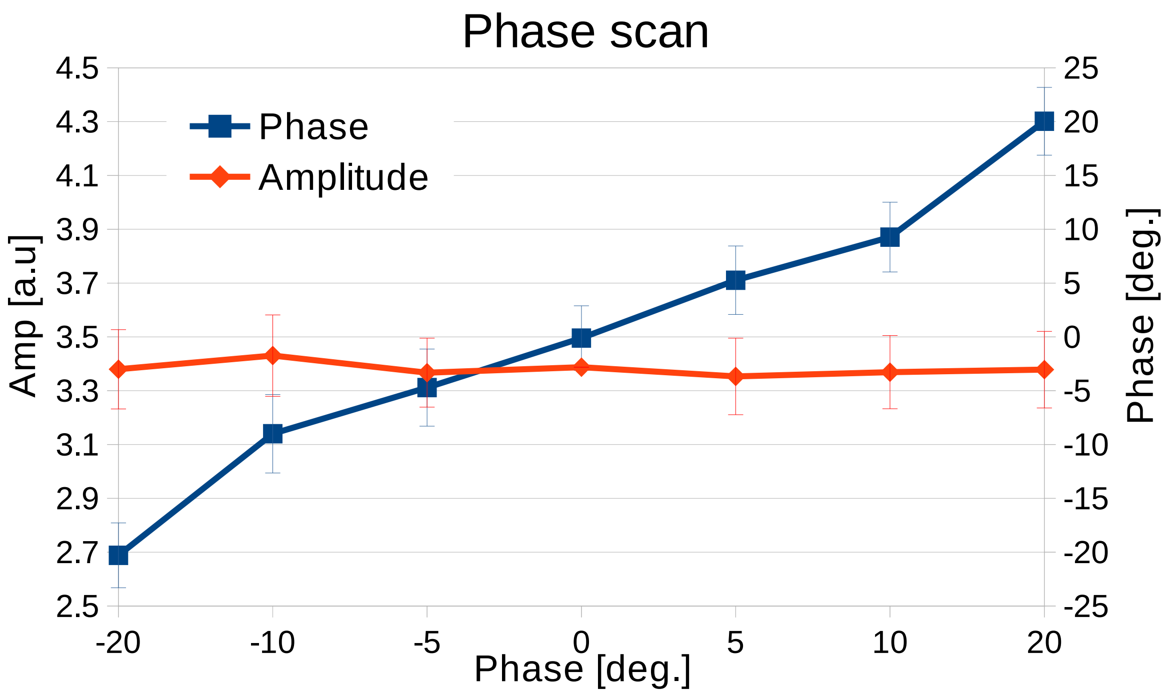
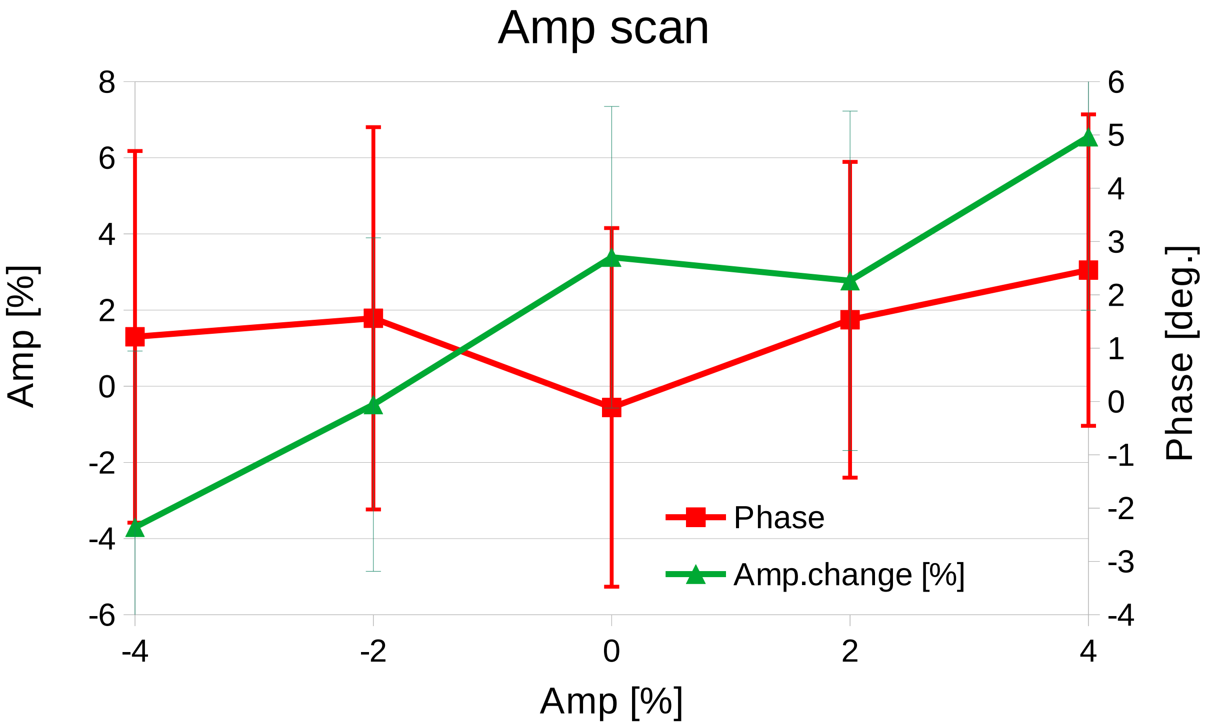
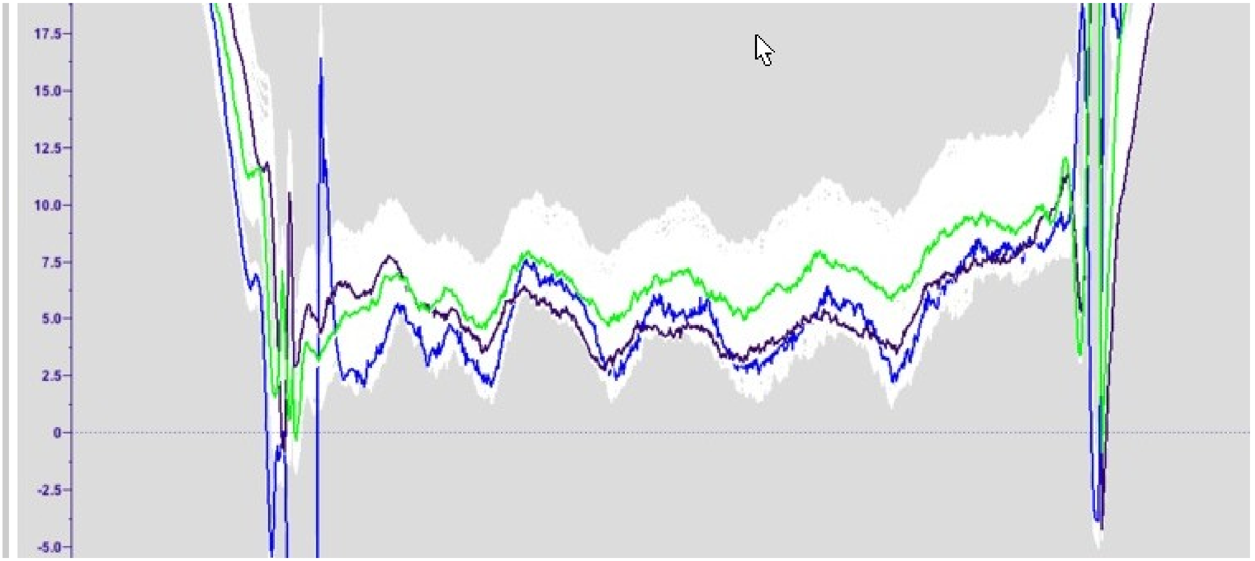




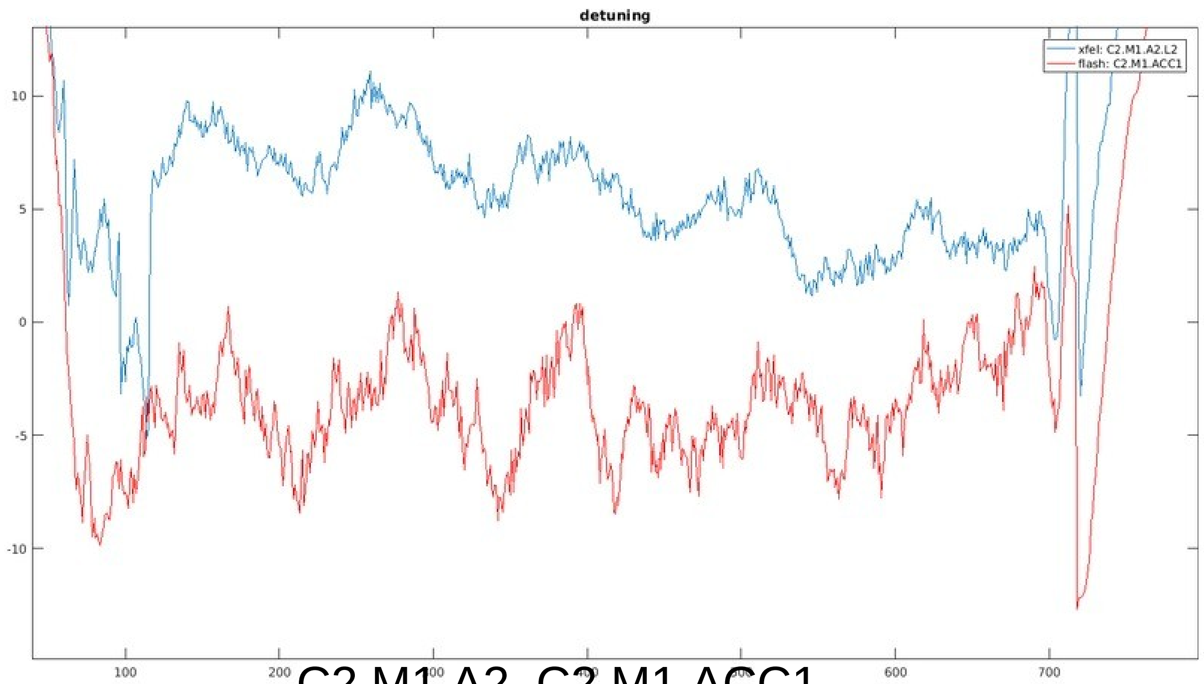
Limitations

Presented results has shown relatively good performance, however not sufficient for beam calibration (the traditional method gives more accurate data). Investigating the possible sources of incorrectness the folowing has been found:

- The cavity detuning always shows ~9kHz oscillations o few Hz amplitude. We discovered these oscillations in all cavities at XFEL and FLASH independently on operating conditions (they are present both in FF and FB). Most probably the reason is a real cavity vibration after beeing pinged with RF.
- Sometimes the RF signal calibration is not fully correct, that generates non-physical jumps in computed detuning waveforms.

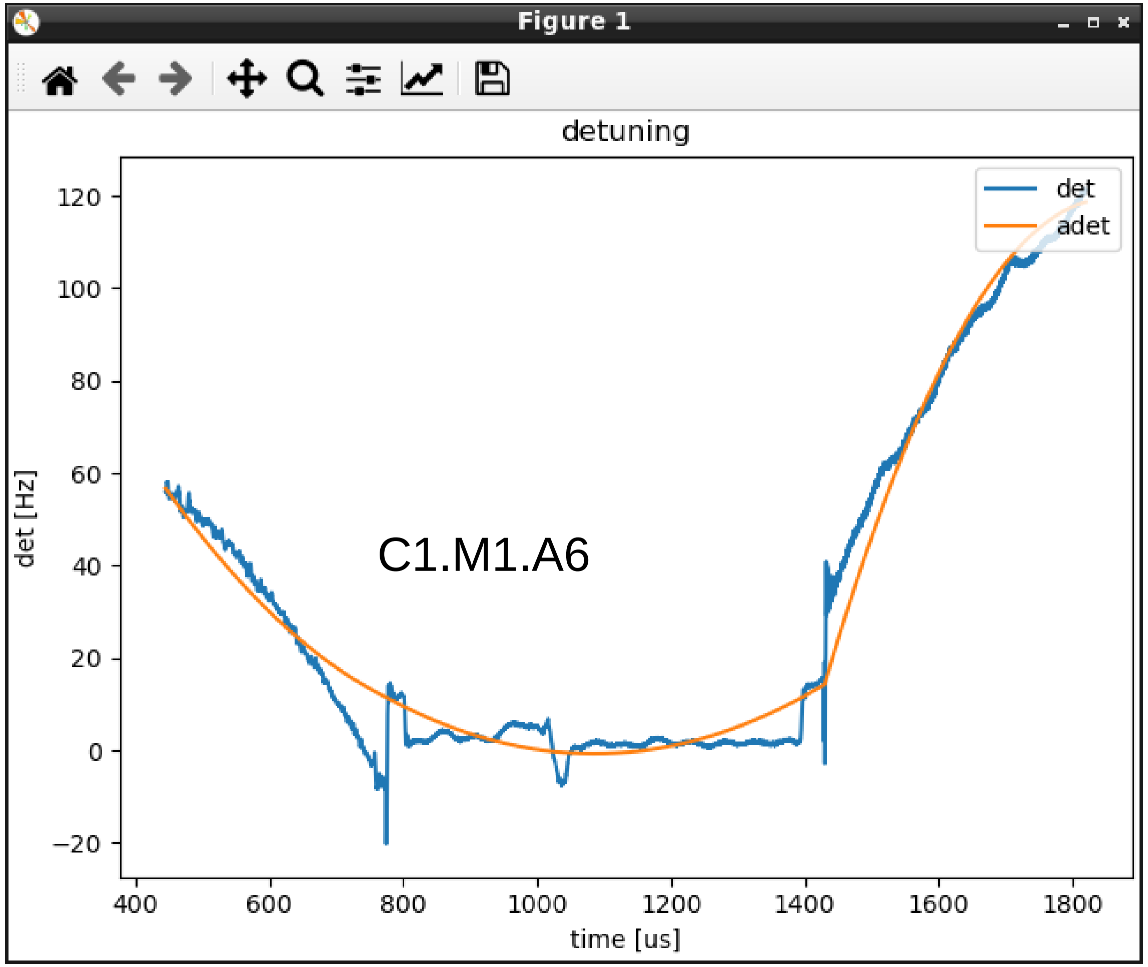


C1.M1.A3, C4.M2.A5 and C5.M2.A23

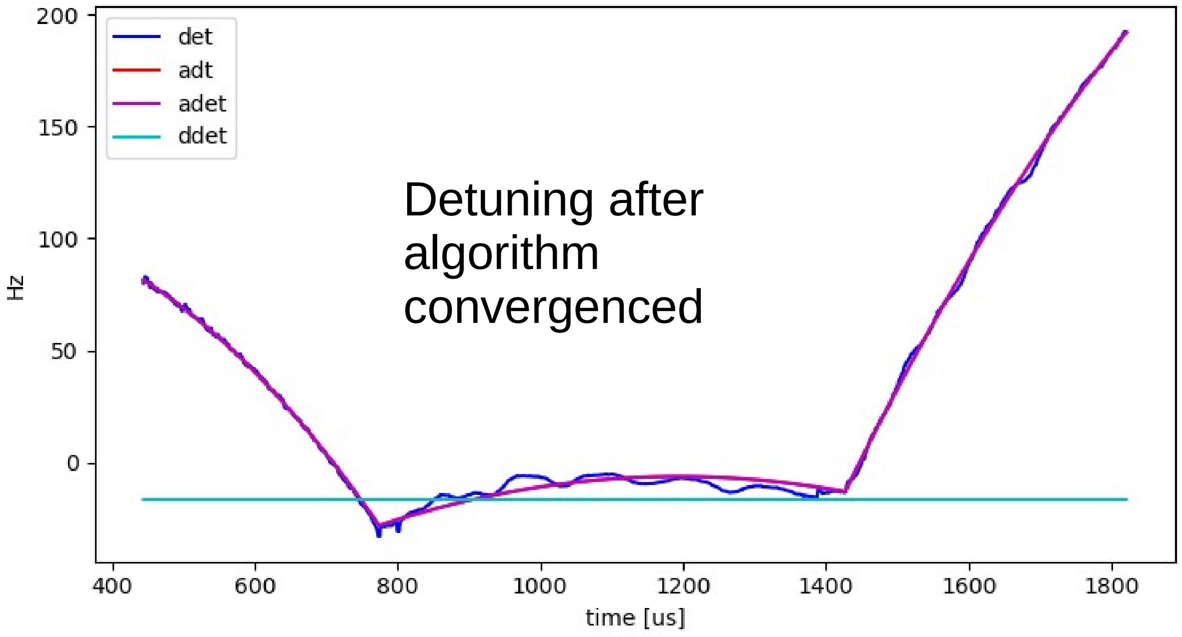


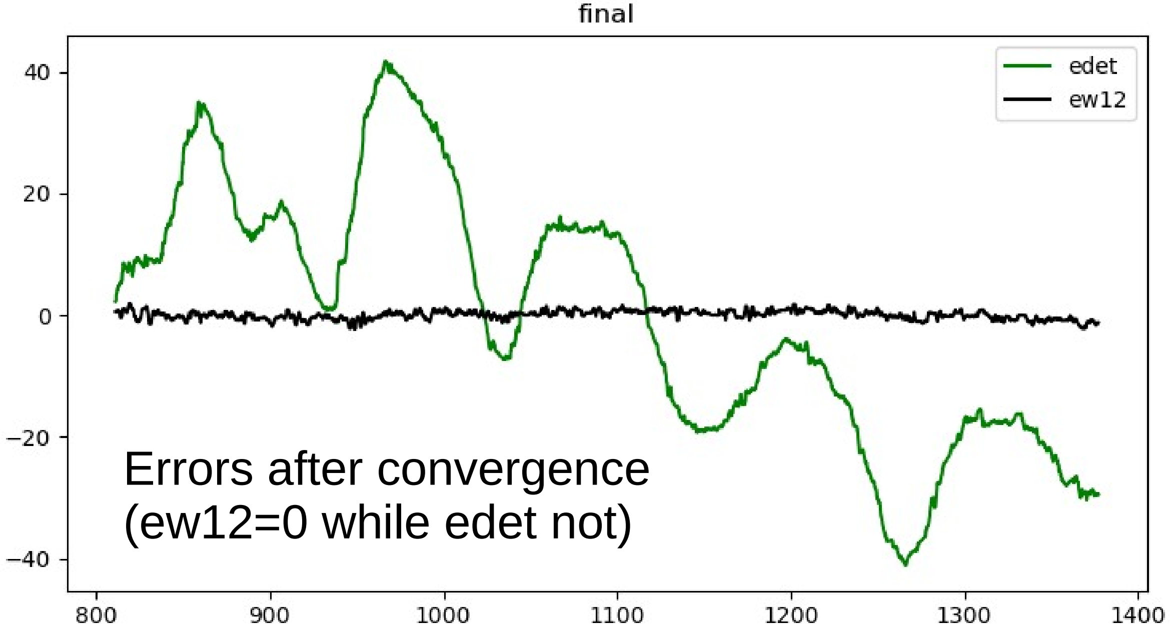
C2.M1.A2, C2.M1.ACC1

Limitations



Problems with detuning computation due to wrong RF signals calibration

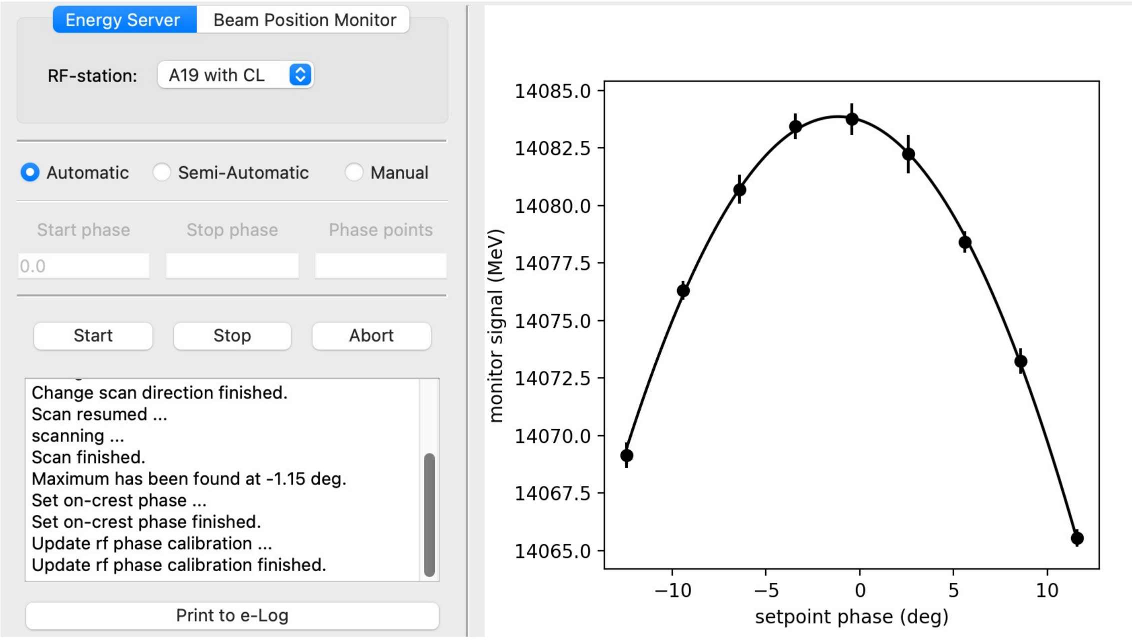


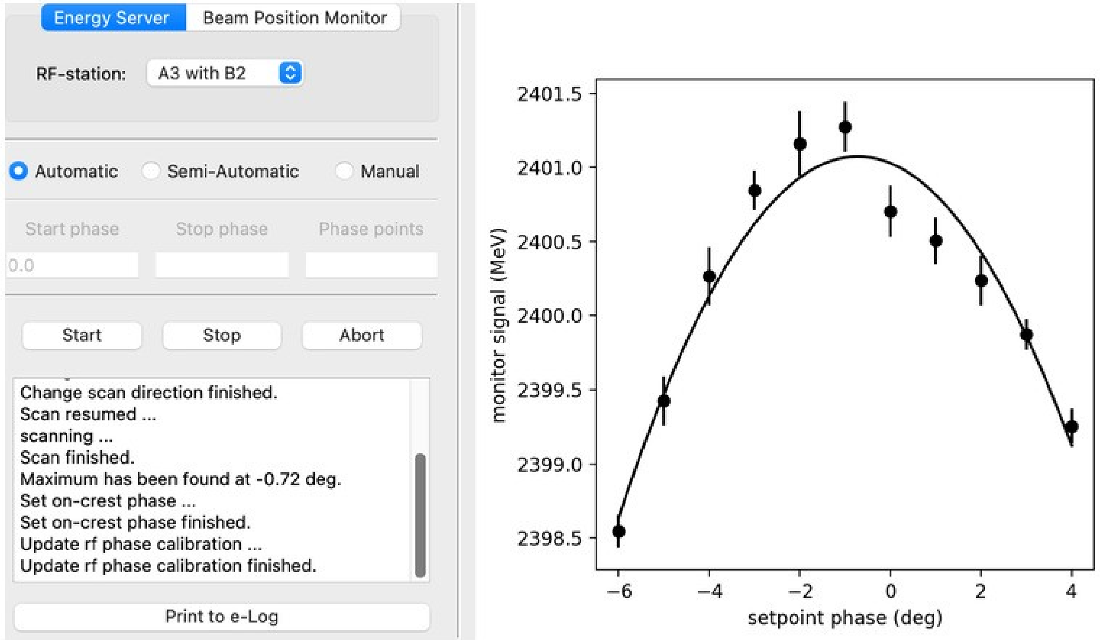


Traditional On-crest phase measurements

Standard method at XFEL and FLASH

- Requires interruption of normal operation and special preparation of the machine
  - No beam-regions allowed
  - Injector must be setup to work in on-crest mode
- Must be made station by station
  - time consuming: ~1h for the whole linac
- Sometimes the accuracy is questionable



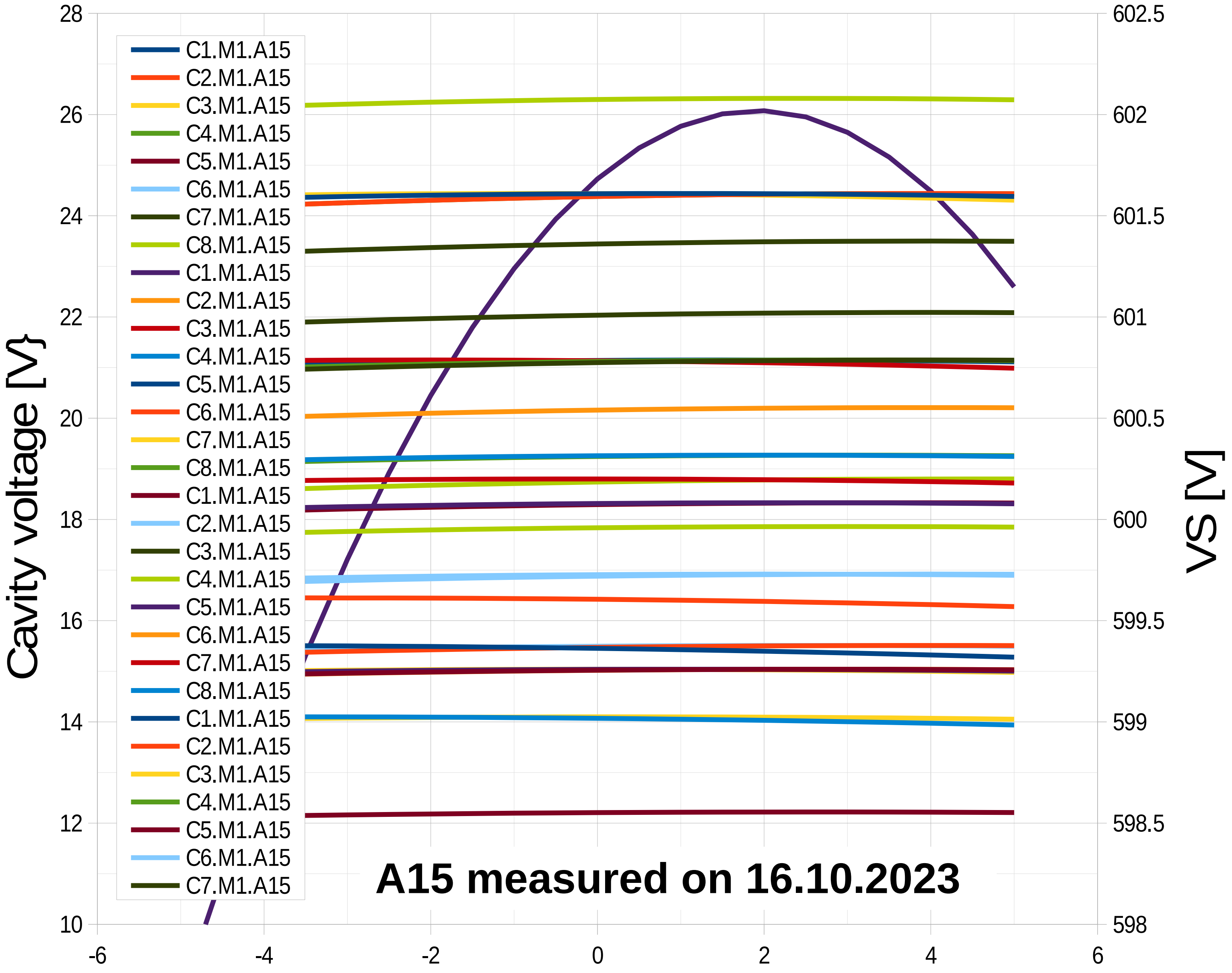


Results

On-crest phase computation basing computed on beam calibration

- A15 measured transparently during normal machine operation
- Vector sum of all the cavity voltage
- On-crest phase: ~2 deg.

This mode of operation is challenging since all the cavities in single station should be processed simultaneously
Unfortunately, even the Fujitsu server has not enough memory to run.
The computations have to be serialized and only ~5 cavities can be processed at a time.



Conclusion

- The beam calibration algorithm was implemented in the multiprocessing python program.
- The currently achieved accuracy is still not high enough to use it to setup machine but it seems adequate to monitor LLRF system state and notify operators when beam phase jumps or drifts away.
- Identified error sources are:
  - Presence of ~9kHz oscillations at detuning during beam time. Probably the cavity is not stiff enough and it vibrates when pingeg by RF. It prevents the optimization algorithm from full convergence.
  - Wrong RF signal calibration in some cases.
  - There are possible also other problems: cross-talks between RF signals and nonlinear effects.
- There are still areas for further improvements that possibly increase the accuracy (e.g. better modeling of beam induced voltage, better detuning approximation).
- Further optimization may focus on reduction of memory consumption. It may also benefit rewriting the program witch C++. Python memory management is not available for the user.

Thank you

Contact

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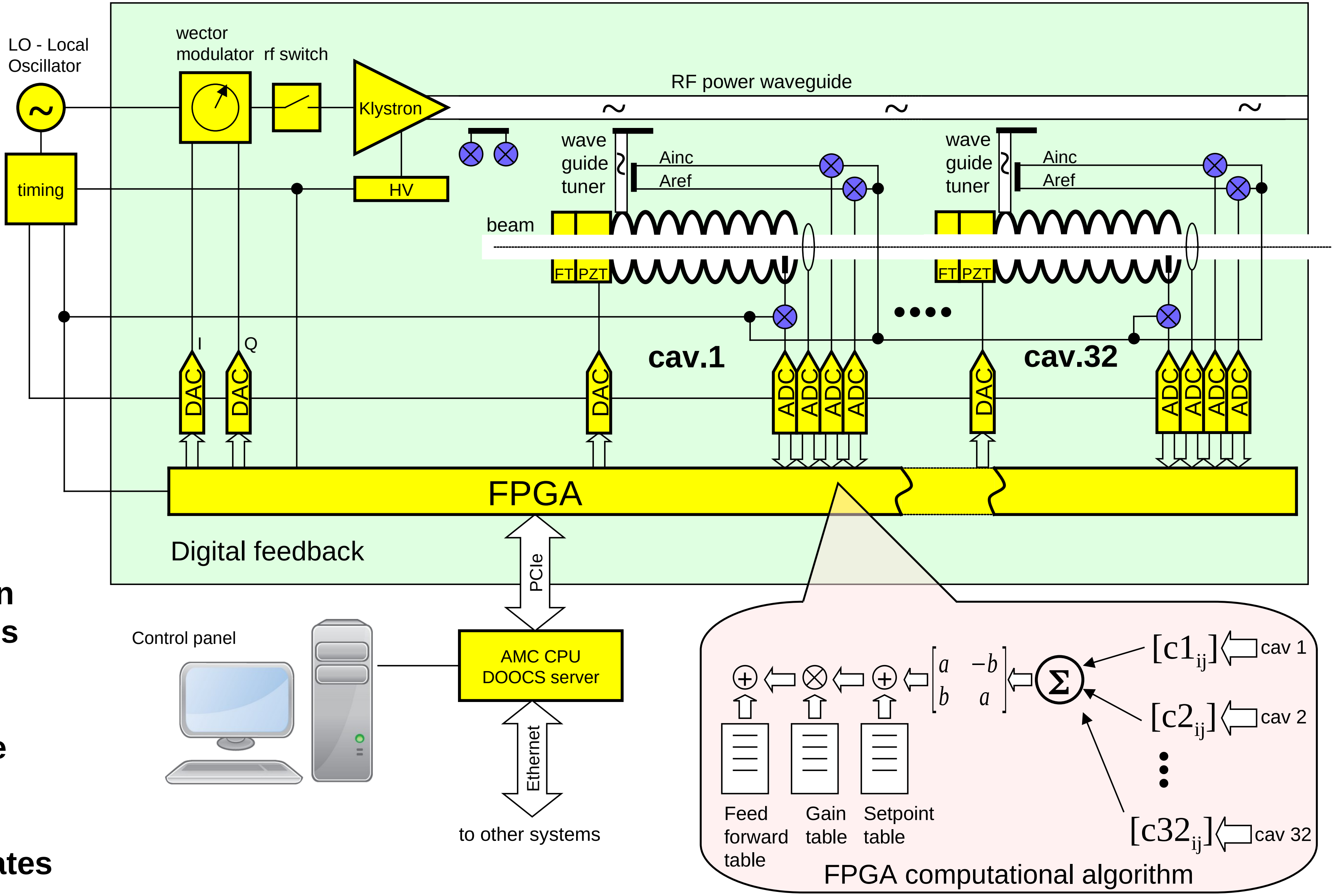
LLRF system architecture

closed loop including cavity

- **cabling**
- **analog front end (DCM, DWC)**
- **A/D conversion (ADC)**
- **digital transmission (subordinate->main)**
- **digital processing (FPGA)**
- **D/A conversion (DAC)**
- **RF modulation (VM)**
- **preamplifier**
- **klystron**
- **waveguides**
- **coupler**



The digital control is implemented in MTCA crate, the processing power is provided by FPGA.

We observe the drifts and the phase jumps in the machine

- **VS calibration slowly drifts**
- **"on-crest" phase slowly fluctuates**