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

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Agenda

Method is generally applicable, it references to XFEL only because it was developed there.

01 XFEL linac

- 25 RF stations driving 784 SC cavities
- Vector Sum control
- Requirements for regulation
- Drifts and phase jumps in LLRF system

02 LLRF system at XFEL

- Architecture of LLRF system at XFEL
- Signal flow

04 Beam calibration

- Measurements using beam loading transients
- On-line measurements

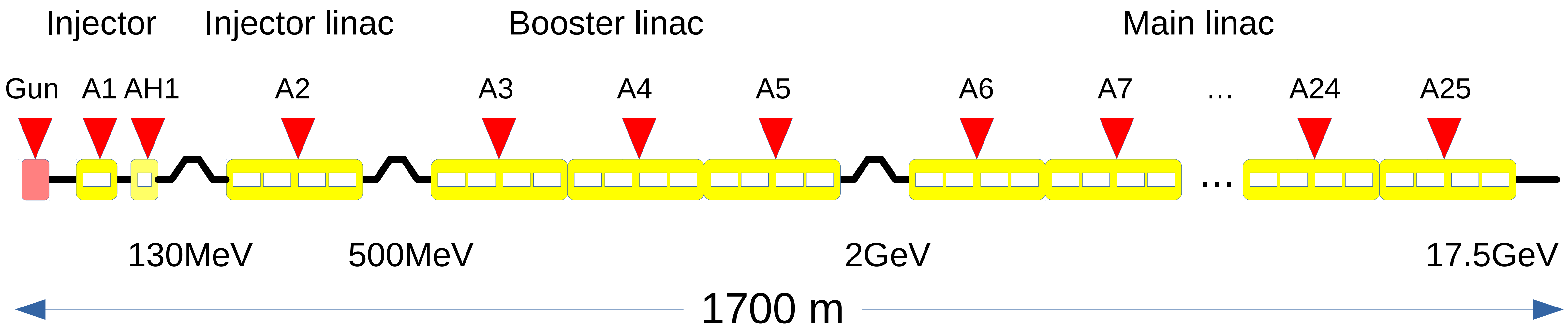
05 Extracting beam calibration from RF and toroid signals

- Cavity equation and signals
- Beam induced cavity voltage
- Algorithm principle
- RF signals calibration
- Detuning approximation
- Errors definition

06 Results

07 Conclusion

XFEL linac



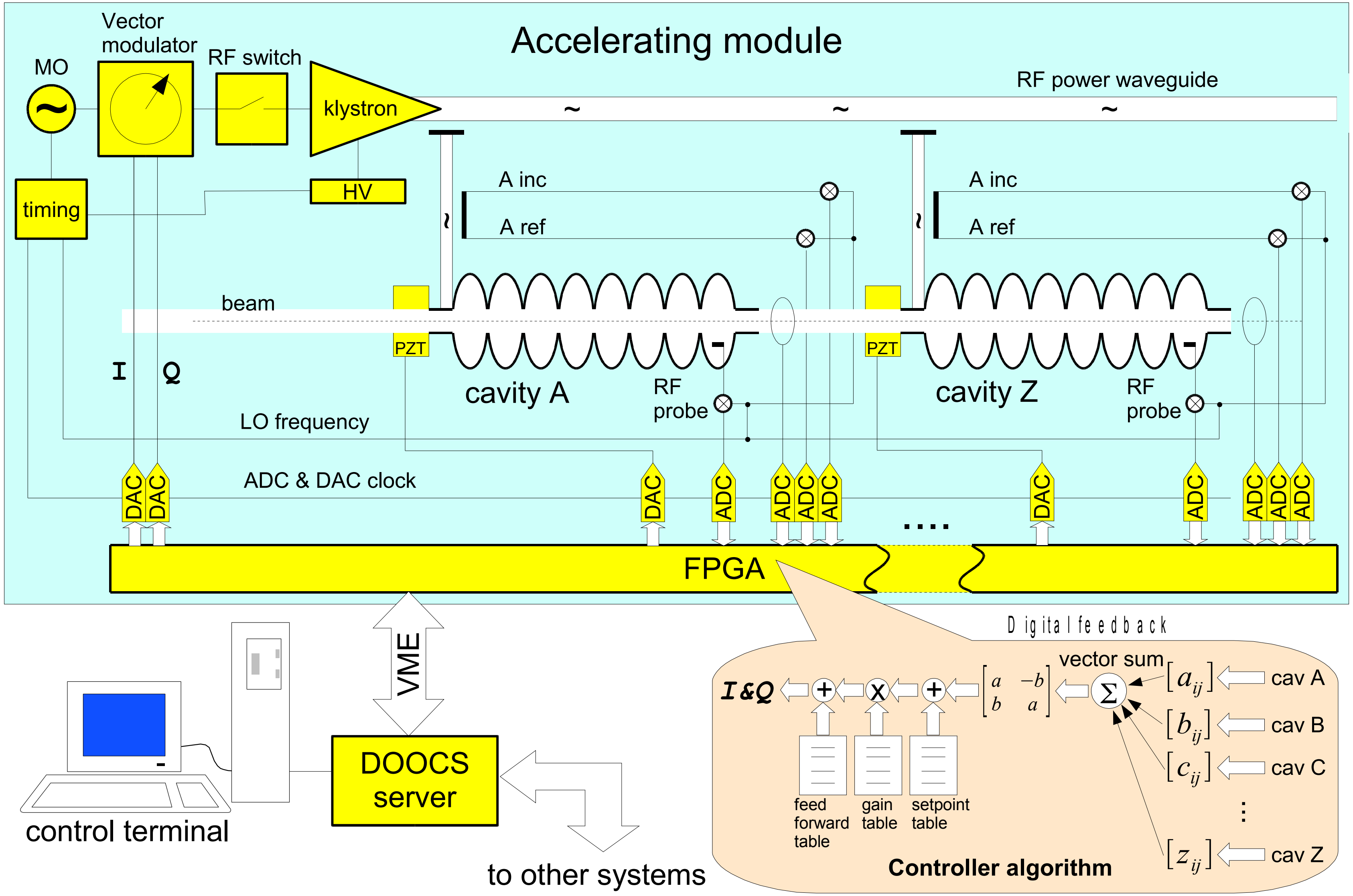
- RF Gun
- 2 RF stations with 8 cavities
- 24 RF stations with 1.3GHz 32 TESLA type cavity each
- in total 784 cavities and 26 RF sources (only SC cavities)
- XFEL requirements for field stability: 0.01% for amplitude and 0.01 deg. for phase

- We observed the drifts and the phase jumps in the machine
  - VS calibration slowly drifts
  - “on-crest” phase slowly fluctuates
  - sometimes the phases between the modules jumps (clocks)
- Until they are noticed and corrected they affect machine performance.

LLRF system architecture

closed loop including

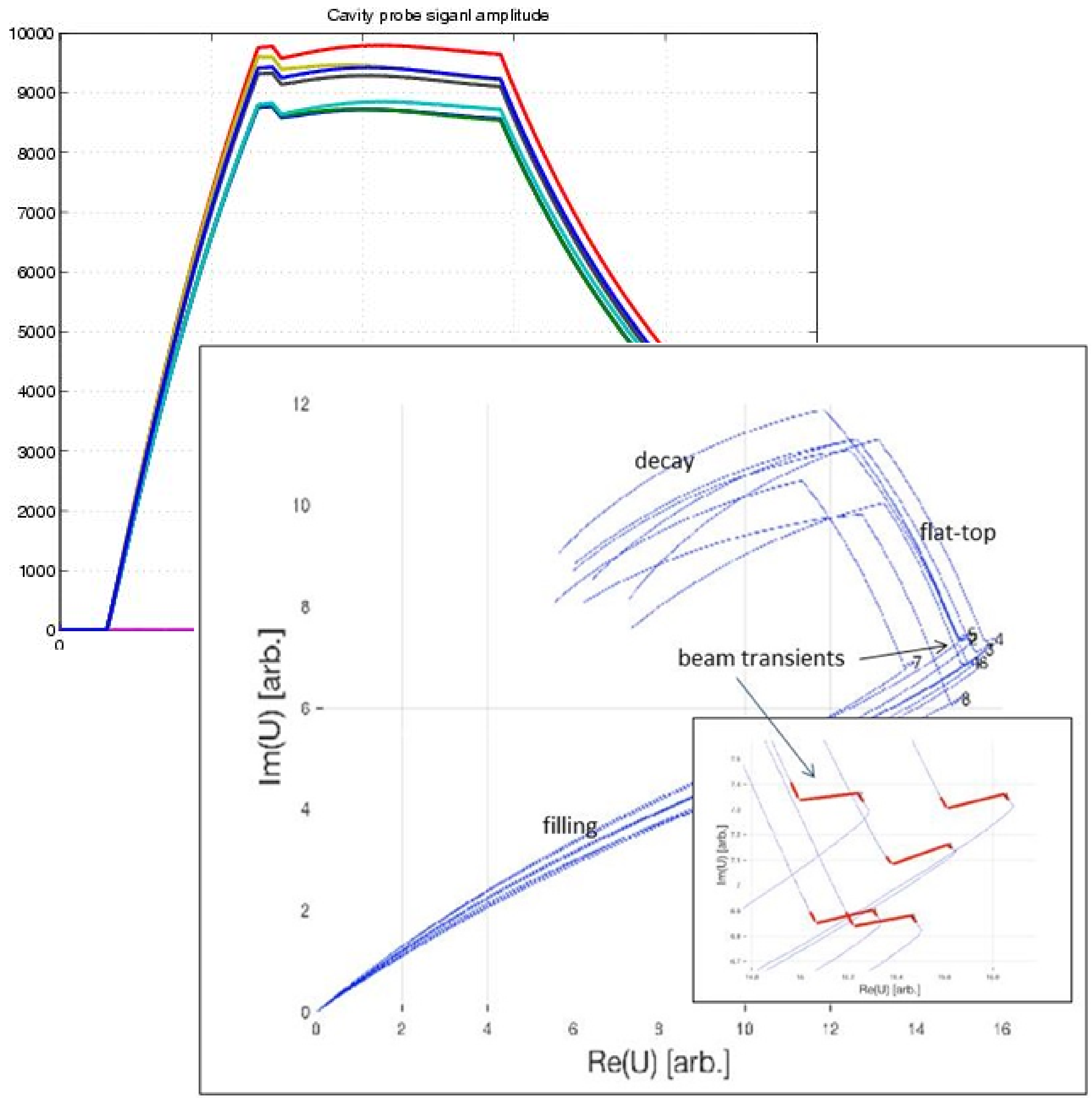
- **cavity**
- **cabling**
- **analog front end (DCM, DWC)**
- **A/D conversion (ADC)**
- **digital transmission (slave->master)**
- **digital processing (FPGA)**
- **D/A conversion (DAC)**
- **RF modulation (VM)**
- **preamplifier**
- **klystron**
- **waveguides**
- **coupler**



VS calibration

Standard method at XFEL and FLASH

- Requires to interrupt normal operation
- Run station in FF only mode
- Allow short bunch train beam (30 bunches, more charge is better)
- Record and analyze probe transients due to beam
- Must be made station by station (time consuming)



Proposal

- Run permanently during normal operation
- It may process many pulses in order to enhance precision through averaging
- Allows to trace changes and drifts in the machine

Cavity math (1)

- Well known cavity envelope equation for base-band
- Using superposition principle one can divide cavity voltage into parts related to forward (V_{cf}) and beam induced voltages (V_{cb})

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

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

$$V_c = V_{cf} + V_{cb}$$

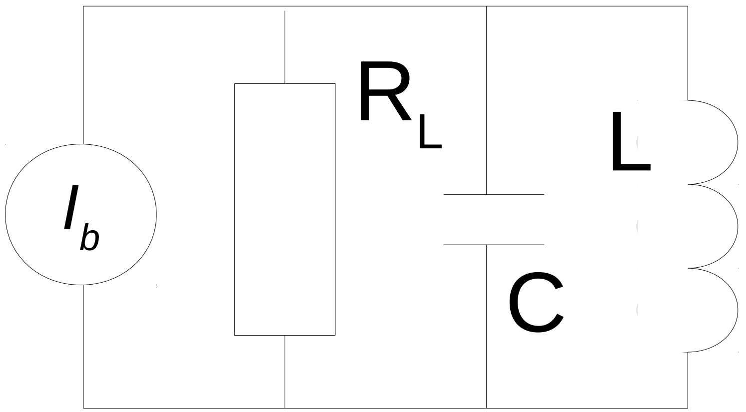
$$\frac{dV_{cb}}{dt} = -(\omega_{1/2} - i\Delta\omega)V_{cb} + 2\omega_{1/2}V_b$$

$$\frac{dV_{cf}}{dt} = -(\omega_{1/2} - i\Delta\omega)V_{cf} + 2\omega_{1/2}V_f$$

Cavity math (2)

- Beam current is assumed to be in the form of Dirac pulse sequence
- For regular bunch trains it is usually transformed to RF envelope as a DC current (I_b=2*I_{bavg})
- For general case one can solve the full 2nd order equation for resonance circuit obtaining the cavity voltage component related to each individual bunch
- After usual simplifications ($\omega_{1/2} << \omega_0$), assuming $I_b = q\,\delta(t)$ is a Dirac pulse with charge q one obtains the cavity voltage step at time 0. This voltage further oscillates with resonance frequency of the cavity ω_0 (i.e. it depends on cavity detuning) and decaying with $\omega_{1/2}$.
- Transferred to the baseband one finally gets the V_b^δ (response to single bunch) as a voltage step (φ_b is a beam phase)

$$V_b = R_L I_b$$



$$\omega_0^2 = \frac{1}{LC}$$

$$2\omega_{1/2} = \frac{1}{R_L C}$$

$$\frac{dV_b^2}{dt^2} + 2\omega_{1/2}\frac{dV_b}{dt} + \omega_0^2 V_b = 2\omega_{1/2} R_L \frac{dI_b}{dt}$$

$$V_b^\delta(t) = 2\omega_{1/2} q R_L e^{-\omega_{1/2} t}\cos(\omega_0 t)$$

$$V_b^\delta = 2\omega_{1/2} q R_L e^{j\varphi_b}$$

Beam induced cavity voltage

- For the beam current in the form of sequence of Dirac pulses the beam induced voltage is a sequence of voltage steps (each step corresponds to single bunch)

$$V_b^{\delta} = 2\omega_{1/2} q R_L e^{j\varphi_b} = V_{bs}$$

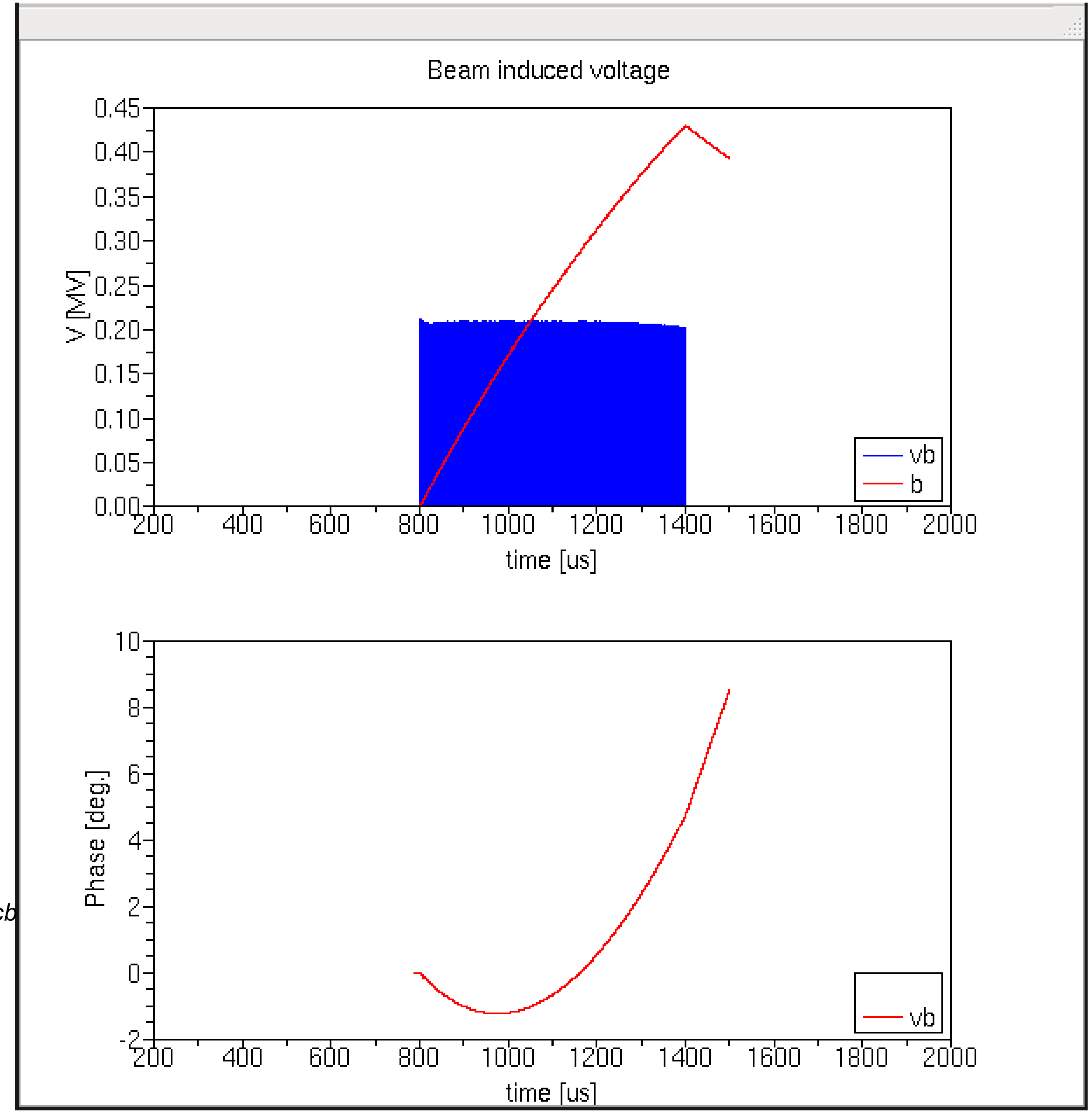
- Between these steps the beam induced voltage decays according the the cavity equation

$$\frac{dV_{cb}}{dt} = -(\omega_{1/2} - i\Delta\omega) V_{cb}$$

$$\forall \text{ bunches} \quad \rightarrow \quad \text{add } V_{bs} \text{ to } V_{cb}$$

- Instead of adding every bunch complex value corresponding to beam phase one can compute the V_{cb} for beam phase equal to 0 and then finally scale the V_{cb} through *bcal* (beam calibration factor – complex)

$$V_{cb} = V_{cb}(\varphi_b = 0) * bcal$$



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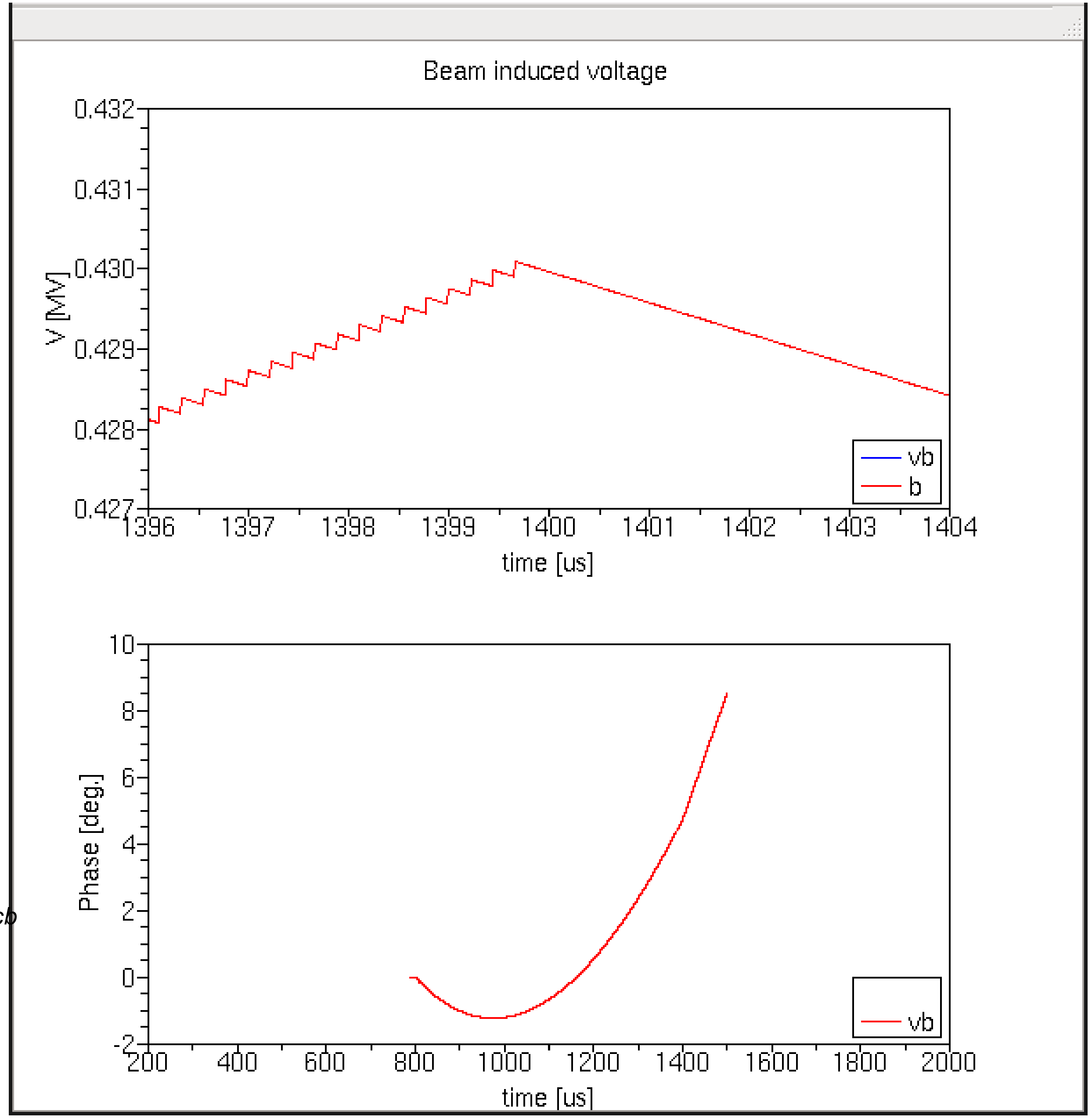

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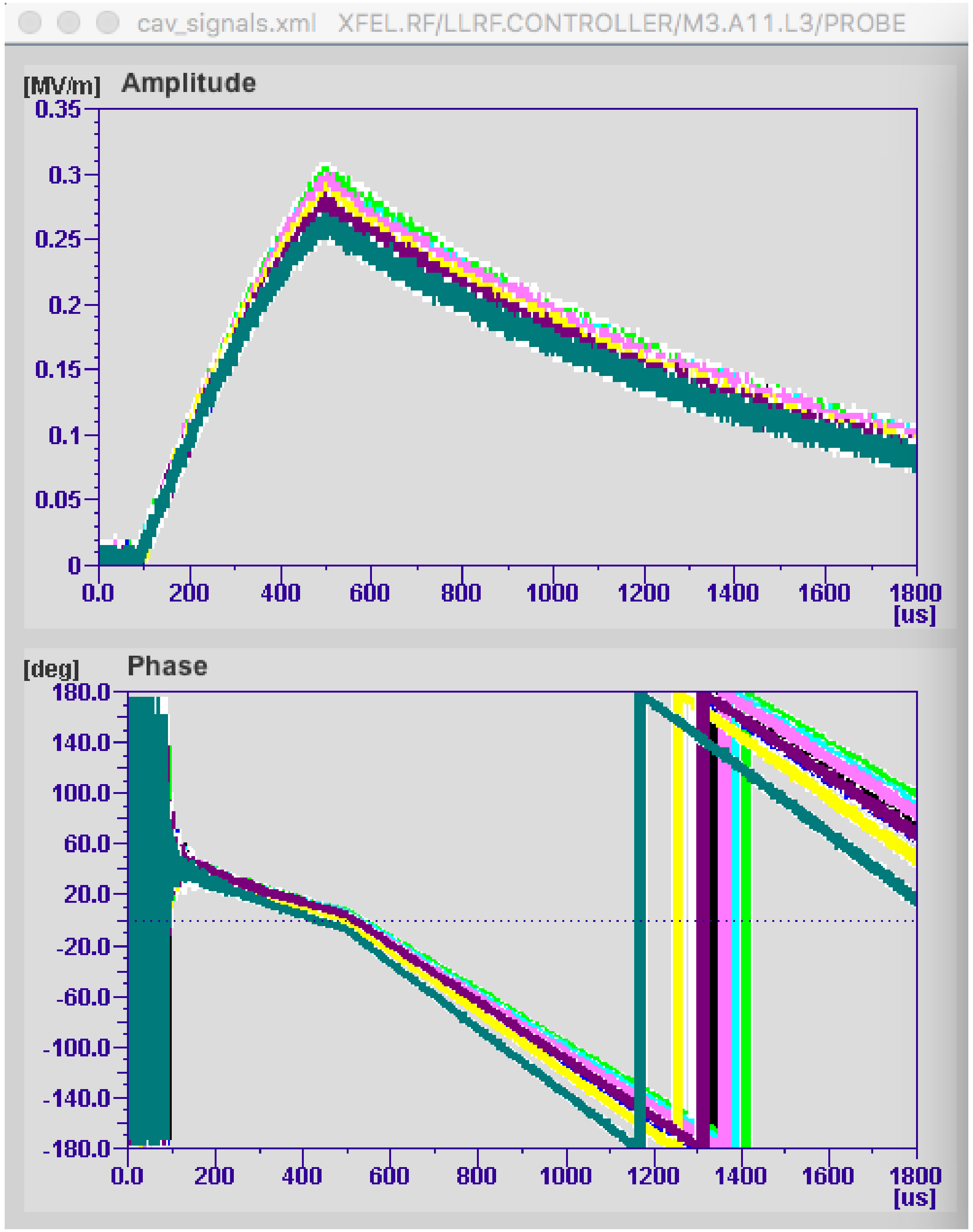
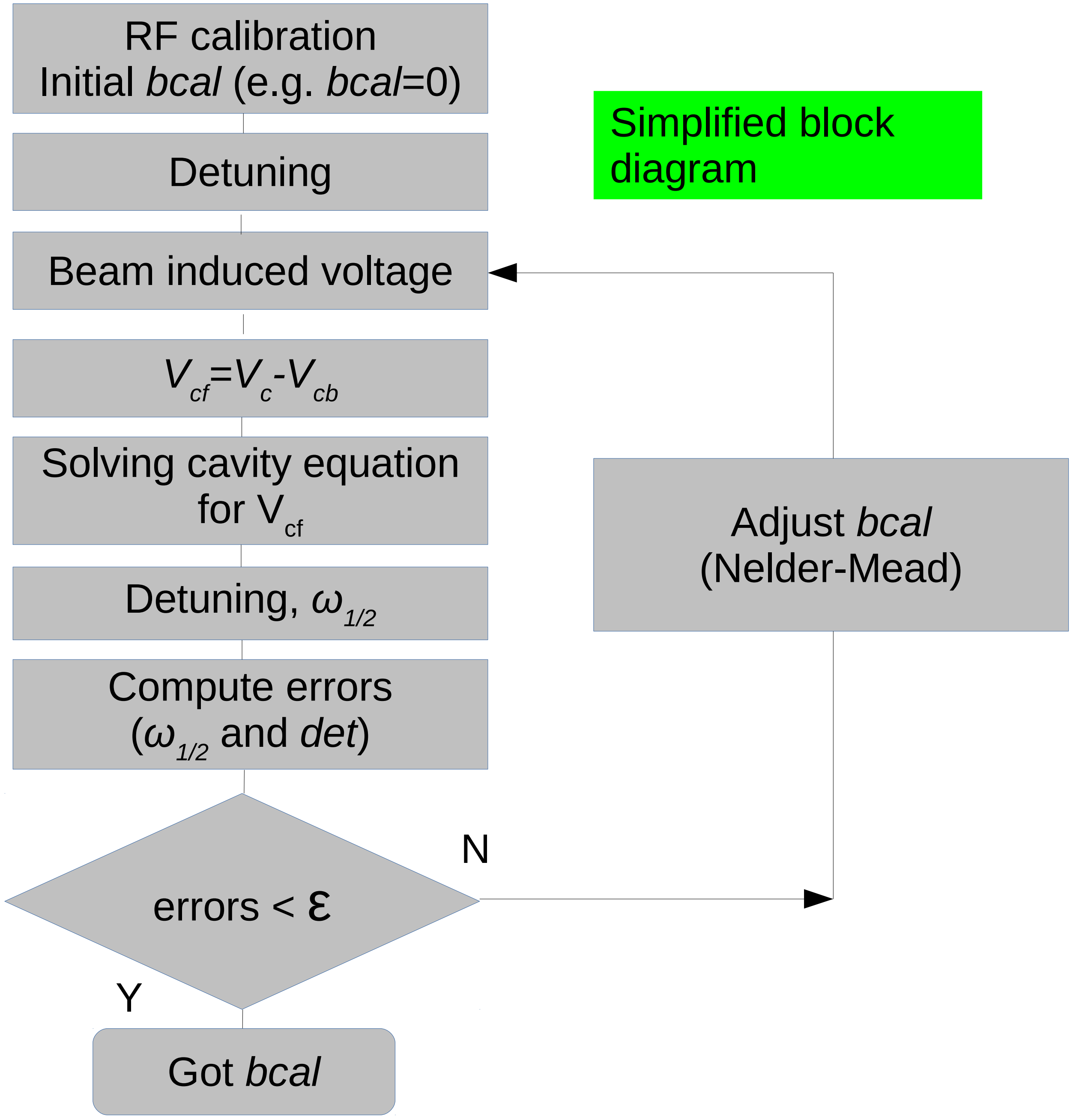


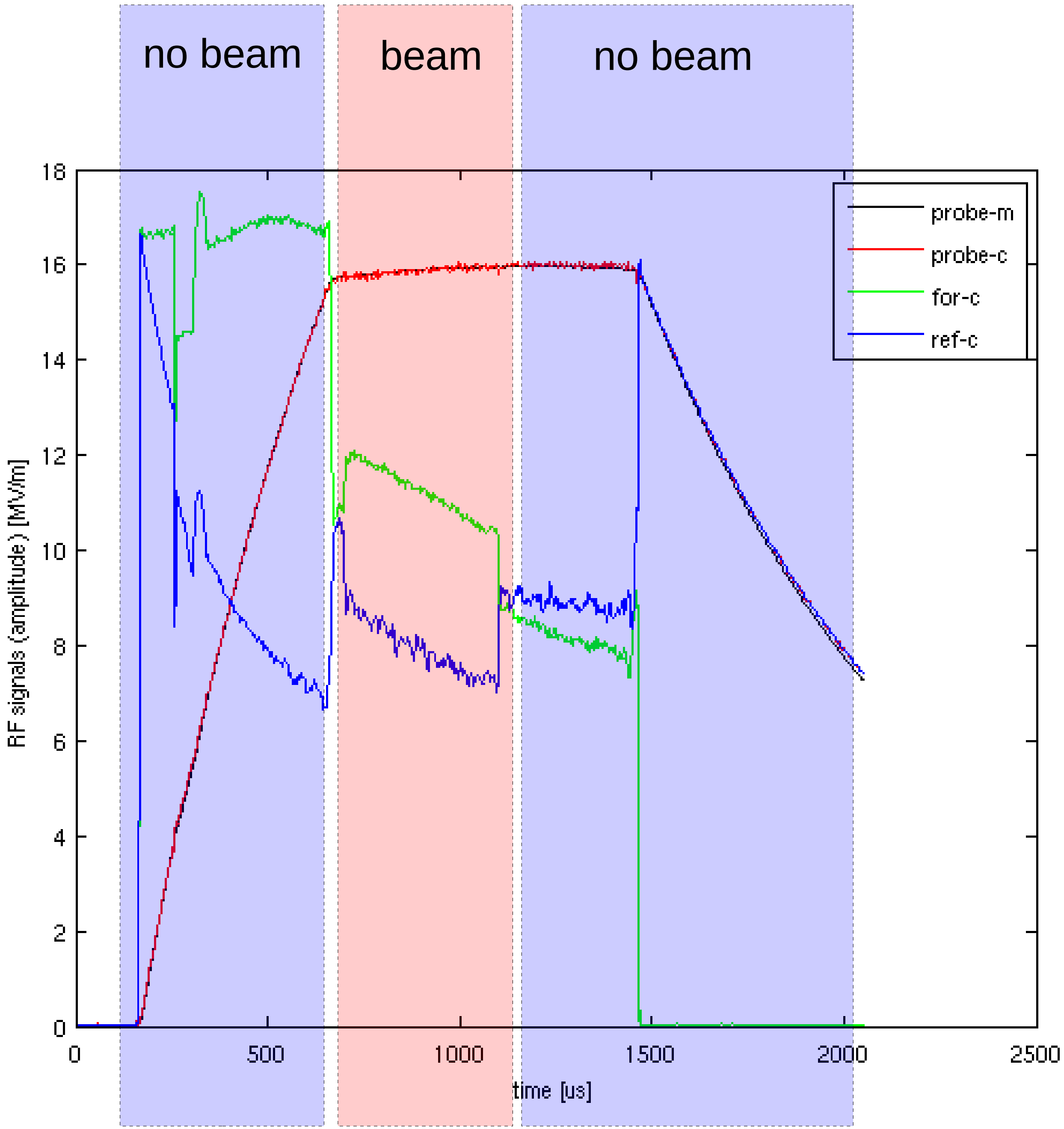
On-line beam calibration algorithm

- The goal is to obtain “*bcal*” - complex factor scaling the beam induced voltage in the cavity equation
- Relies on iterative signal fitting and error minimization



Signals calibration (1)

- Each RF pulse consist of regions without beam (filling, decay and possibly part of flattop) and with beam
- Areas with “no beam” are used for RF signals calibration (initial stage of algorithm)
- Area with beam present is used for beam calibration (main stage of algorithm)



Signals calibration (2)

No-beam conditions

- The $\omega_{1/2}$ can be measured from probe signal slope during decay and it must be constant over the whole pulse
- *X, Y, Z* can be extracted from measured signals
- a can be extracted from condition $\omega_{1/2}$ = const solving cavity equation

$$V_c = r e^{j\varphi}, V_f = \rho^{j\theta}$$
$$\frac{dr}{dt} + r\,\omega_{1/2} = \omega_{1/2}\,\rho\cos(\theta-\varphi)$$

- This way we have all *a, b, c, d*

$$V_f \quad = a\hat{V}_f + b\hat{V}_r$$
$$V_r \quad = c\hat{V}_f + d\hat{V}_r$$
$$V = \hat{V} = V_{for} + V_{ref} = X\hat{V}_f + Y\hat{V}_r$$

$$\hat{V}, \hat{V}_f, \hat{V}_r - measured\ signals$$
$$V, V_f, V_r - calibrated\ signals$$
$$a, b, c, d - calibration\ factors$$

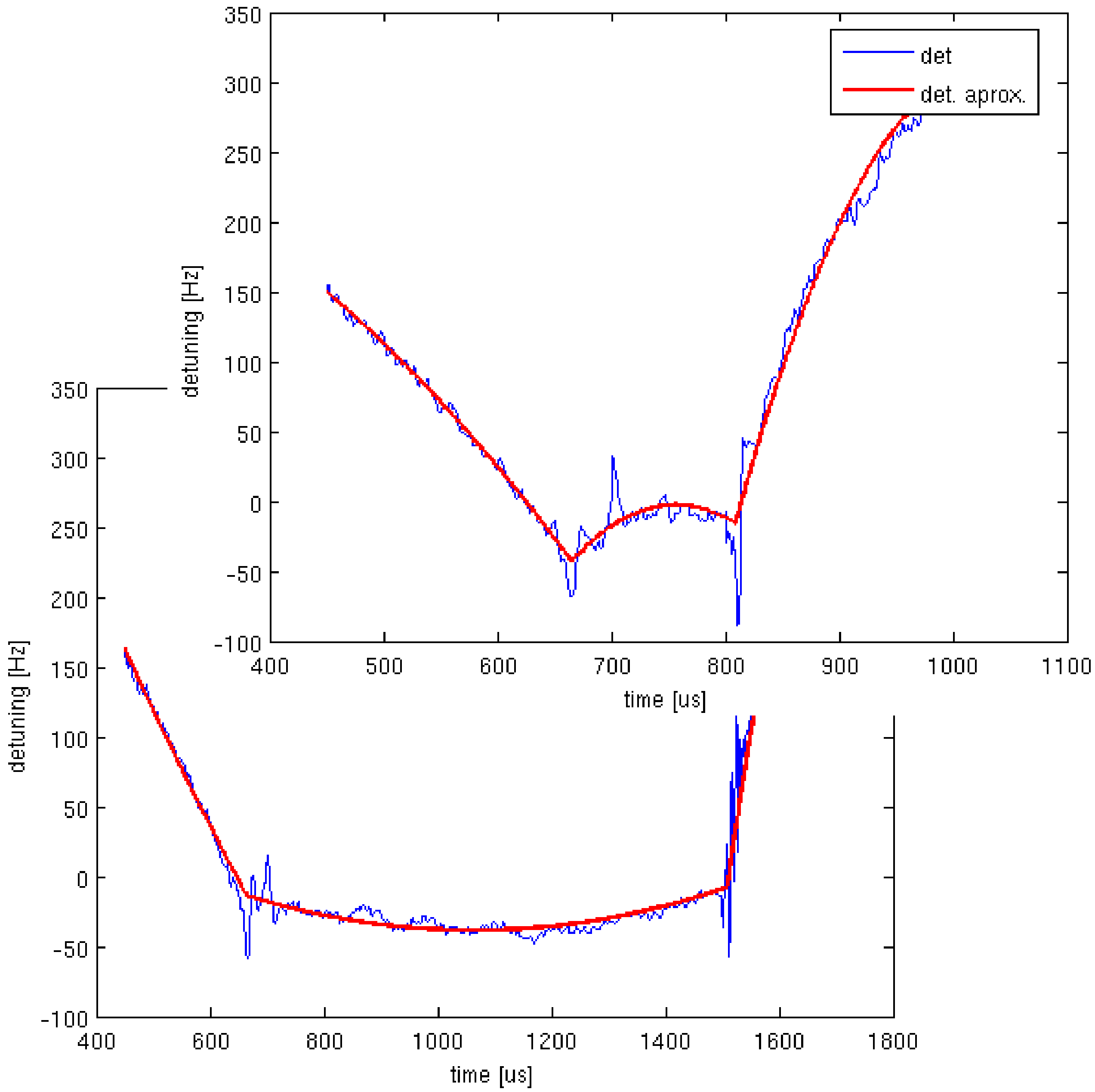
$$Z = \frac{b}{a} = -\frac{V_f}{V_r}$$ when $V_f = 0$

$$b = \frac{a}{Z}$$
$$c = X - a$$
$$d = Y - \frac{a}{Z}$$

Curtessy A.Brand

Detuning approximation

- for the areas without beam one can compute detuning from cavity equation
- it is noisy signal, since it depends on phase derivative. In order to be able to use it in computation one have to approximate detuning with smooth and continuous waveform.
- Good results gives an approximation by 2nd order polynomials separately in filling, flattop and decay.



Error computation

- For approximated Δω and given bunch pattern the beam induced voltage is computed
- From measured V_c and computed V_{cb} the forward voltage related part of cavity voltage is computed
- From cavity equation for V_{cf} the $\omega_{1/2}$ and $\Delta\omega$ are computed (only for the beam region) and compared with expected values.
- All RF signals are averaged using 10 successive pulses. The err signals are filtered using median filter with 20 samples long window.

$$V_{cf} = V_c - V_{cb}$$

$$\frac{dV_{cf}}{dt} = -(\omega_{1/2} - i\Delta\omega) V_{cf} + 2\omega_{1/2} V_f$$

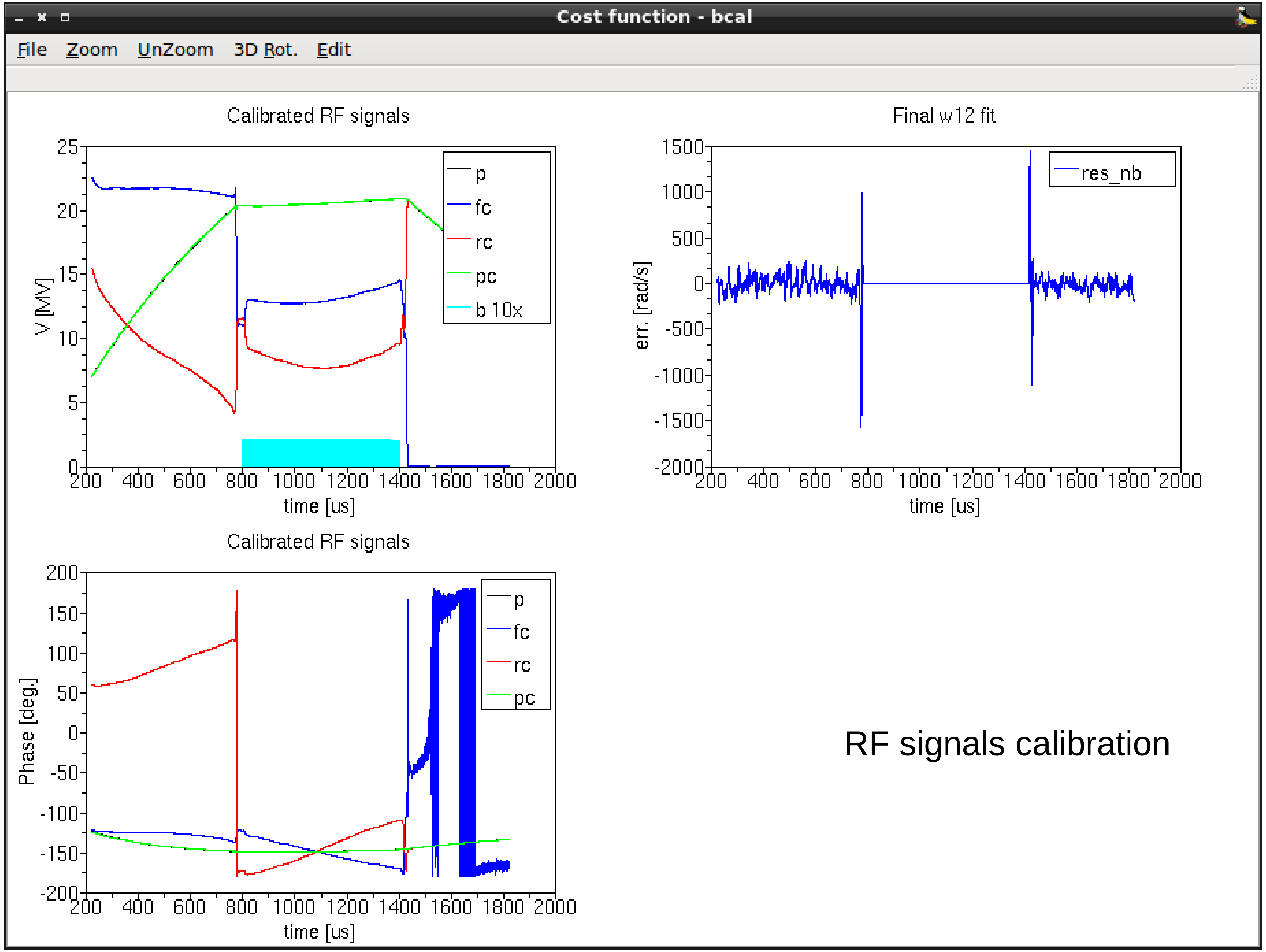
$$(\omega'_{1/2} - i\Delta'\omega) = \frac{2\omega_{1/2} V_f - \frac{dV_{cf}}{dt}}{V_{cf}}$$

$$err_{\omega_{1/2}} = \sum (\omega'_{1/2} - \omega_{1/2})^2$$

$$err_{\Delta\omega} = \sum (\Delta'\omega - \Delta\omega_a)^2$$

Results

C8.A1 @ 140 MV
0.90 mA
(2699 bunches@ 0.2 nC)



RF signals calibration

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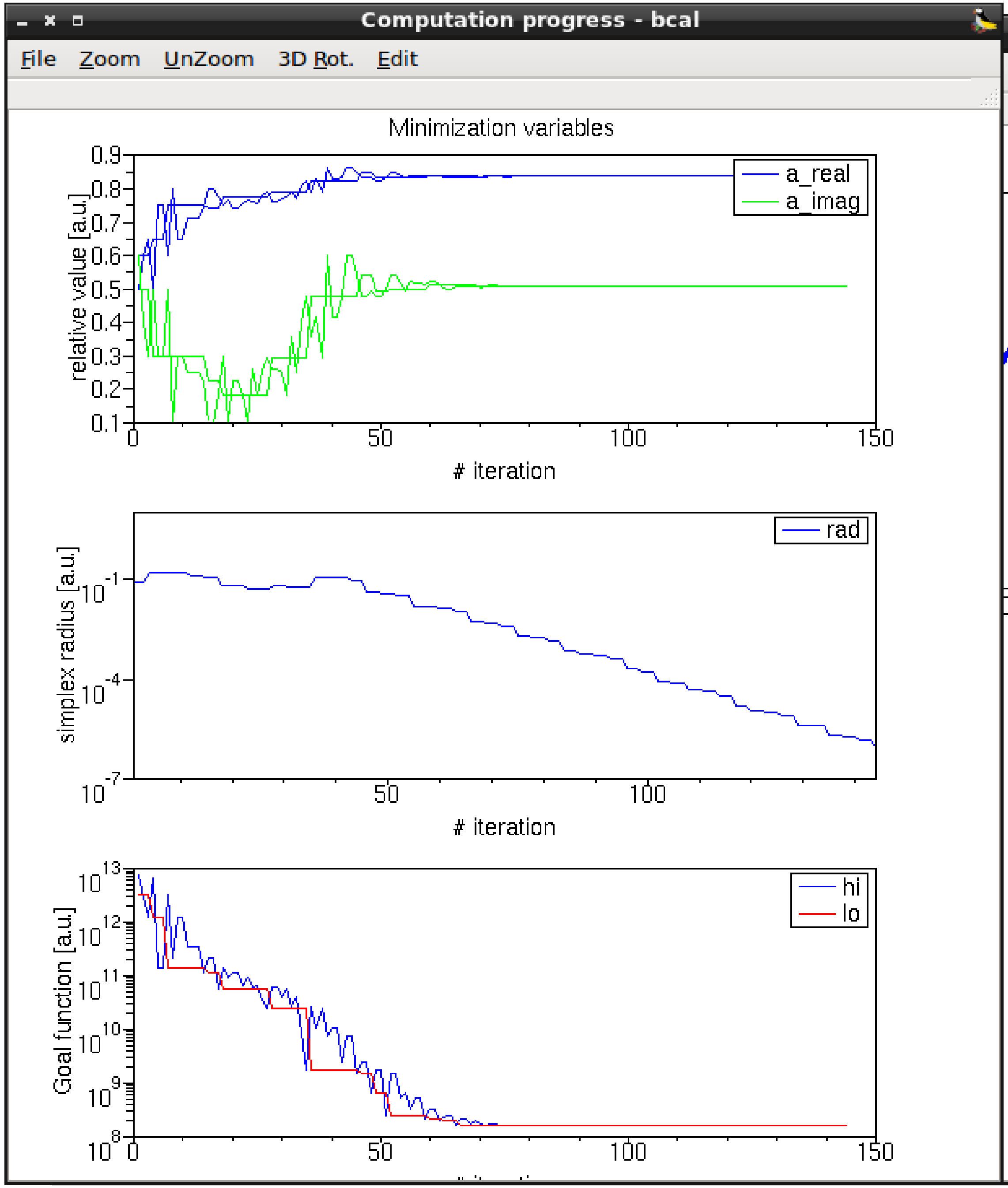
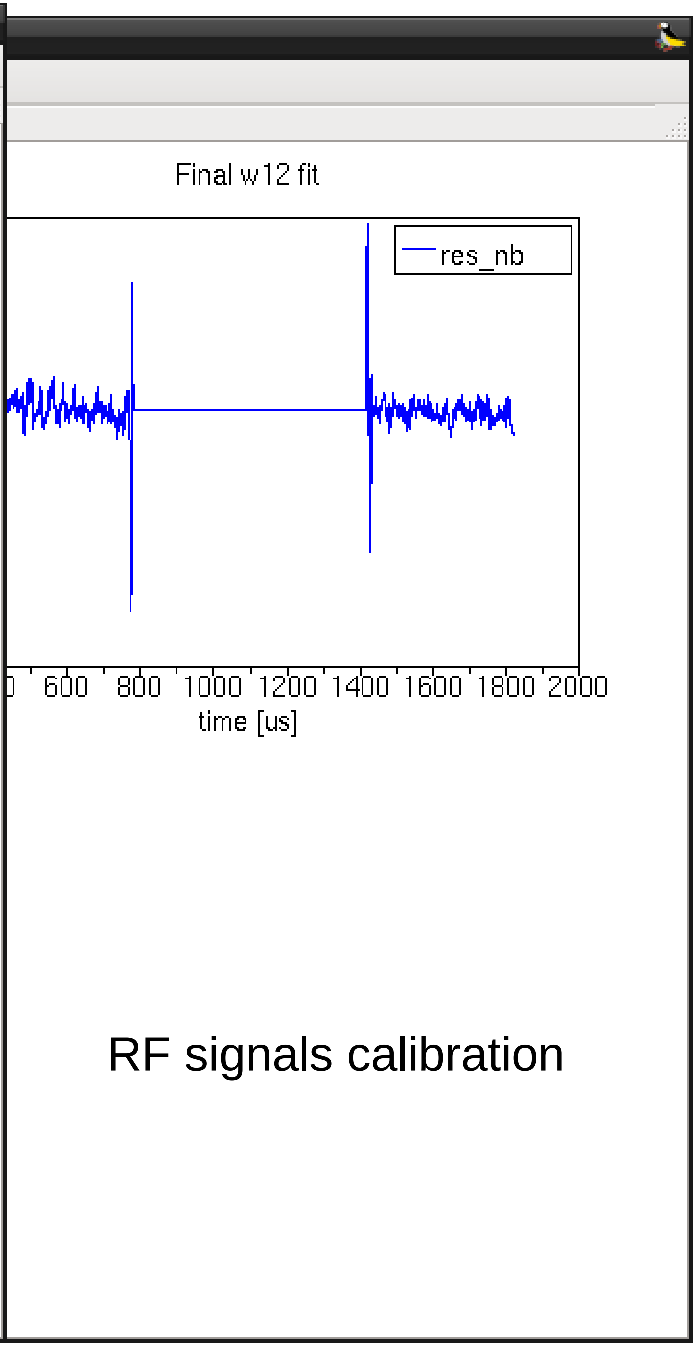


Fitting progress



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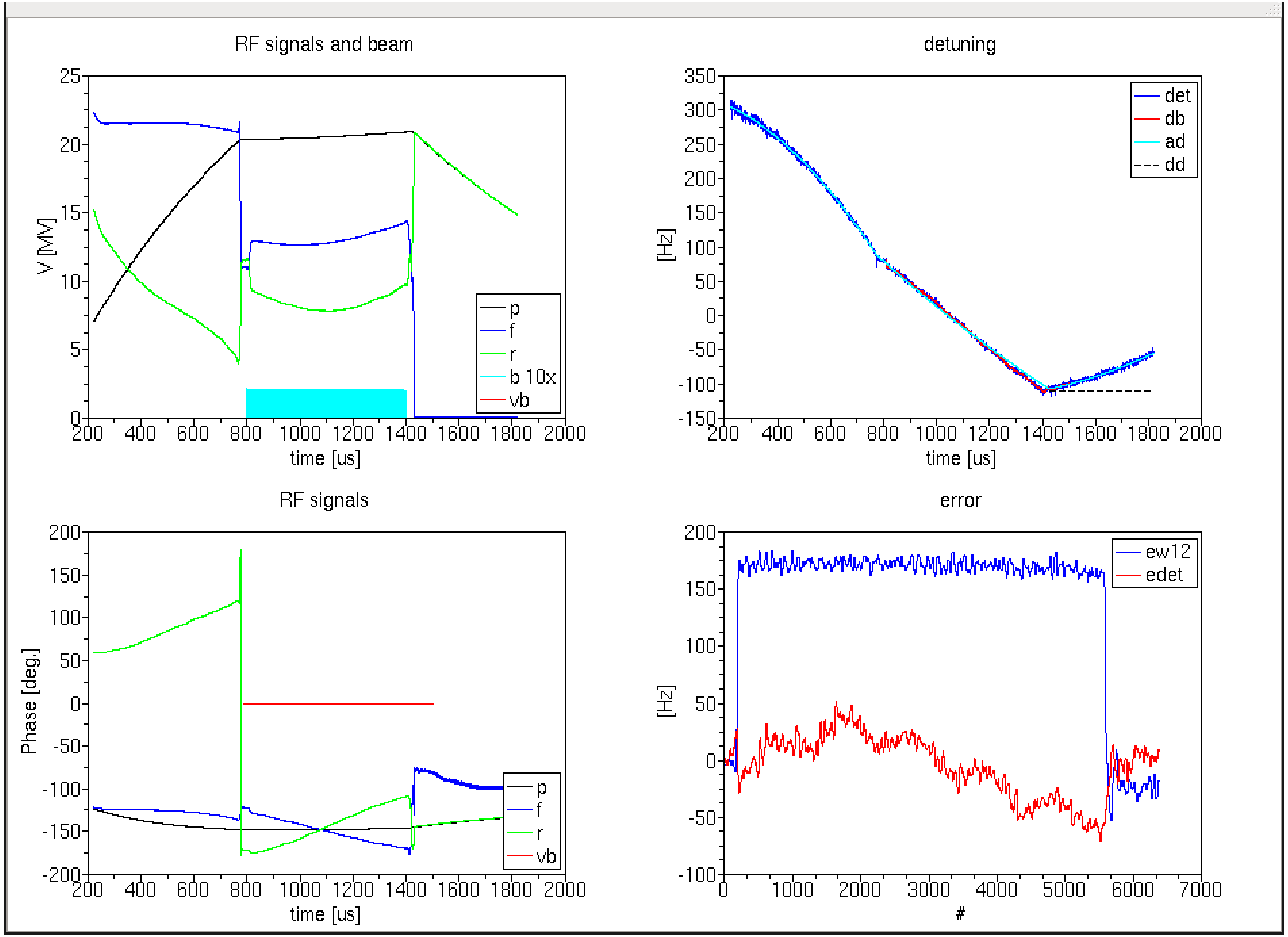

Initial conditions, bcal=0, V_b=0, huge error, particularly at $\omega_{1/2}$

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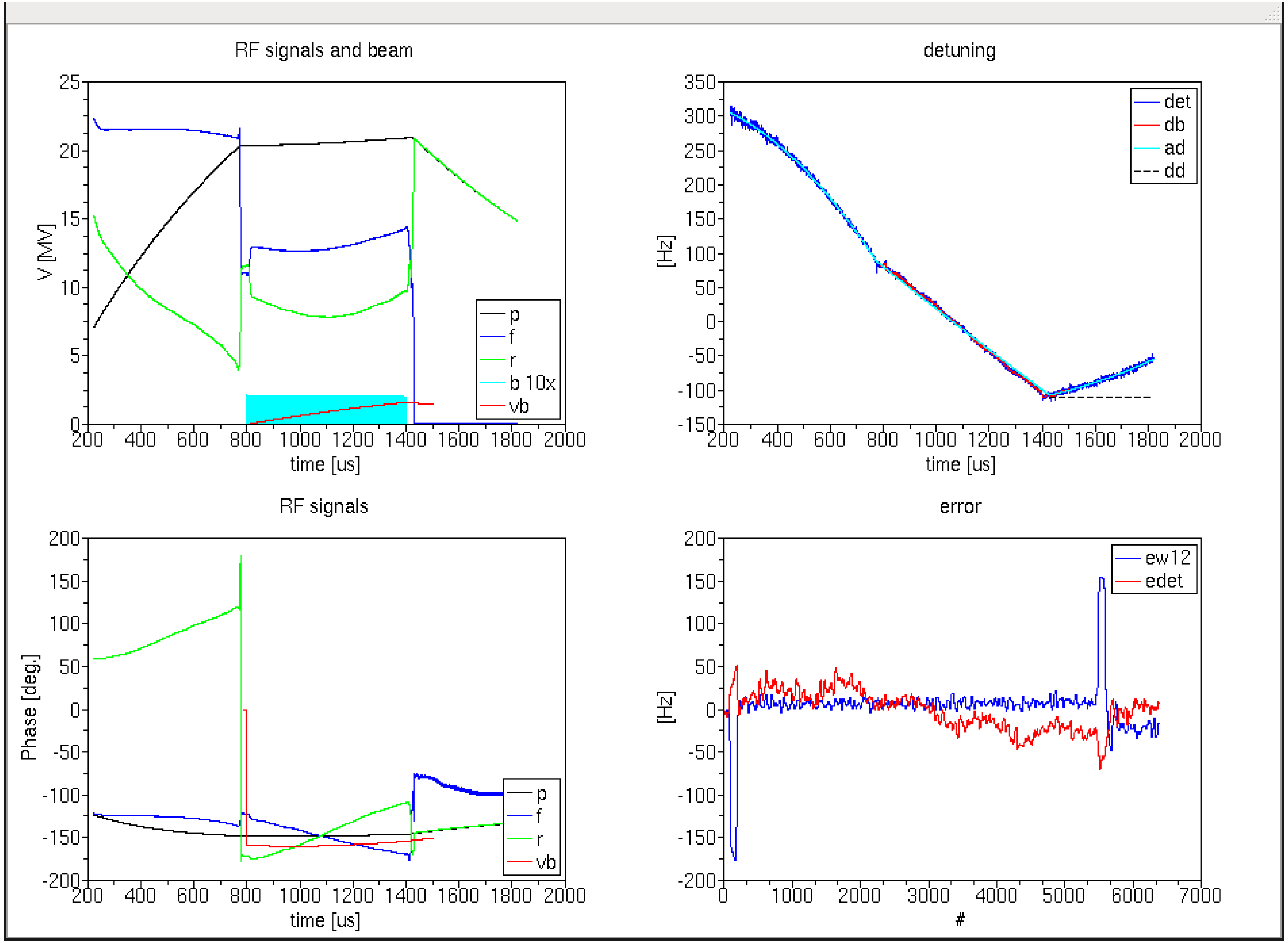
Final fit,
bcal=-3.444 -i*1.327



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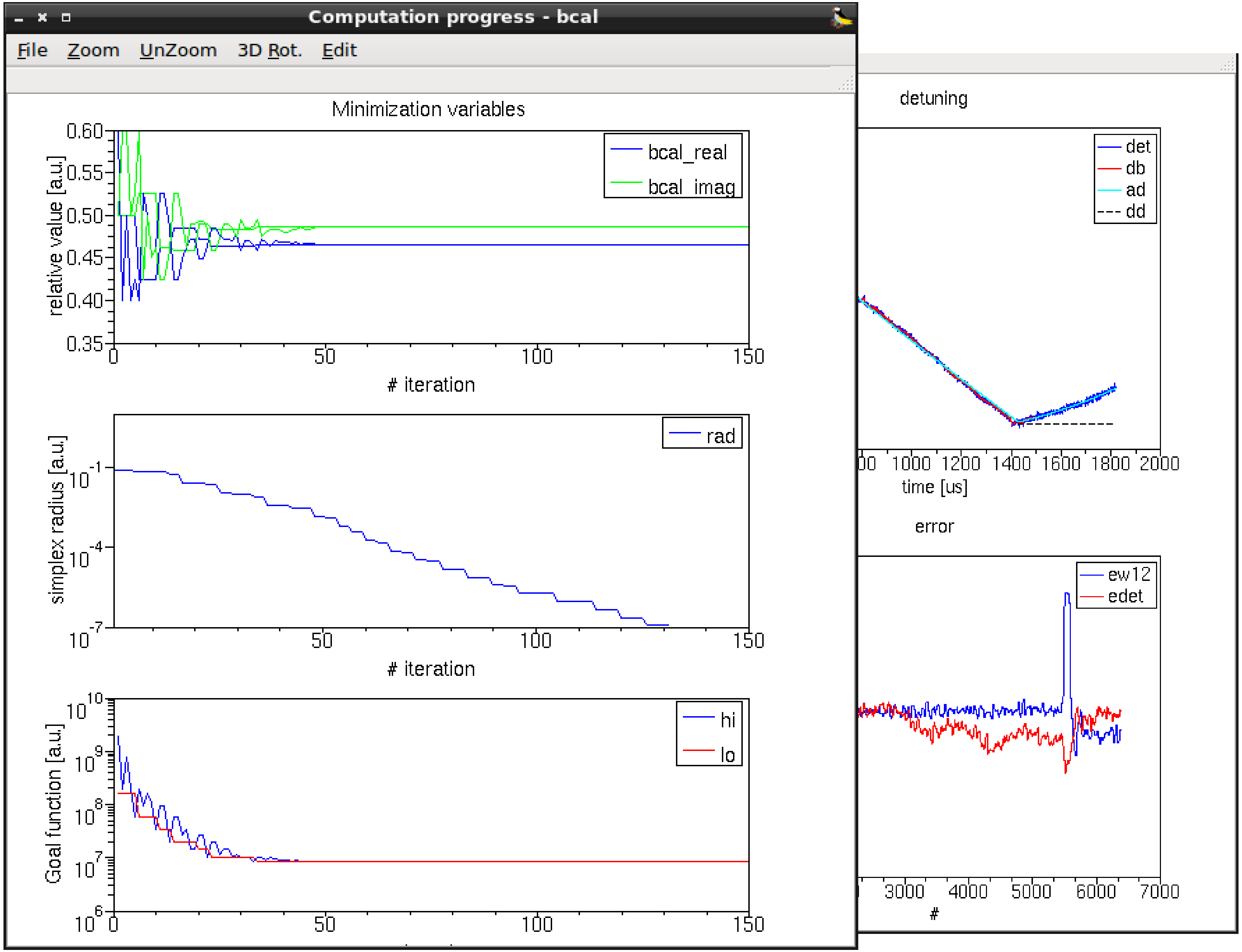
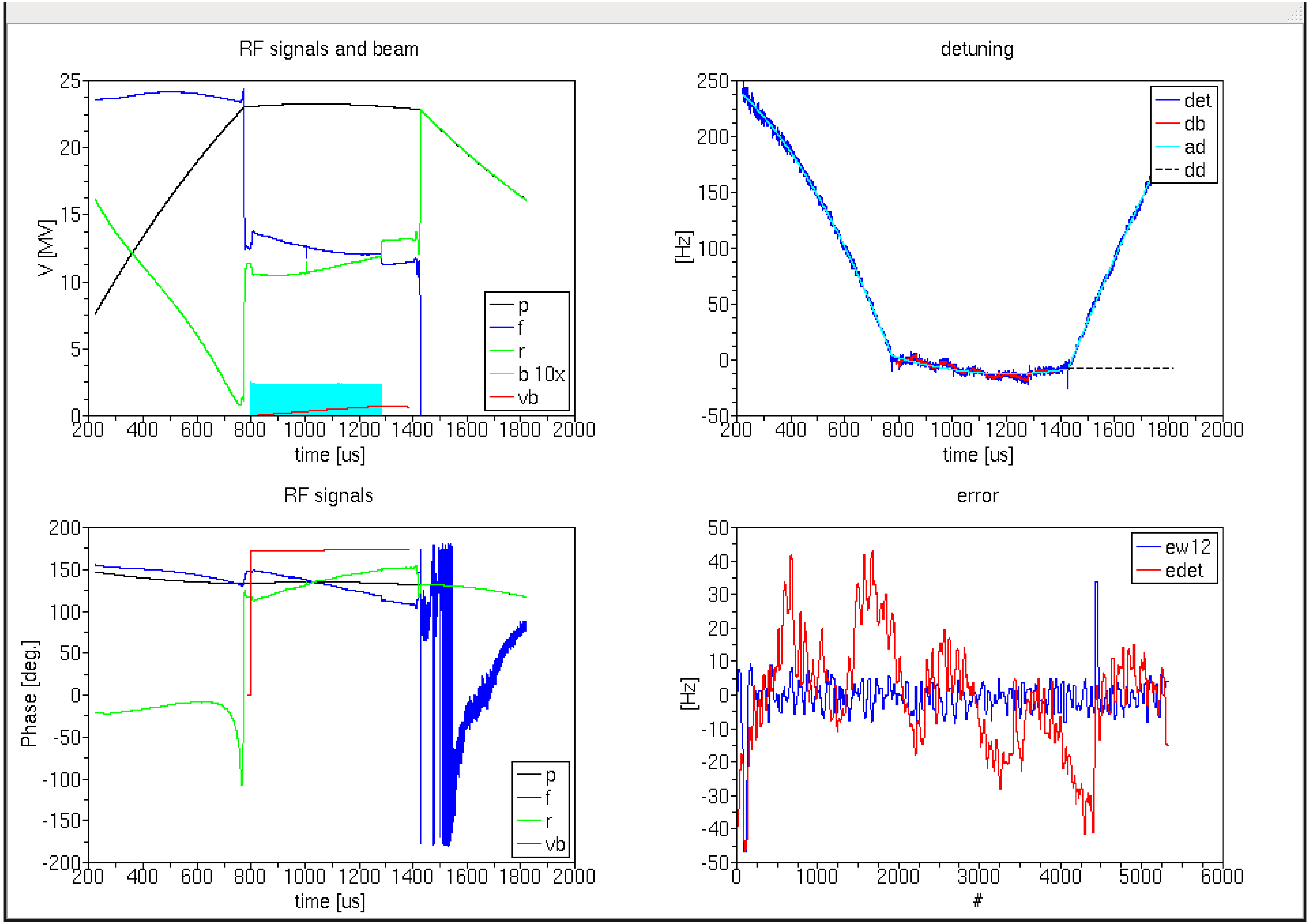


Fitting progress

Results

C3.A15 @ 680 MV
0.55 mA, piezos on
(1015 bunches@ 0.25 nC)

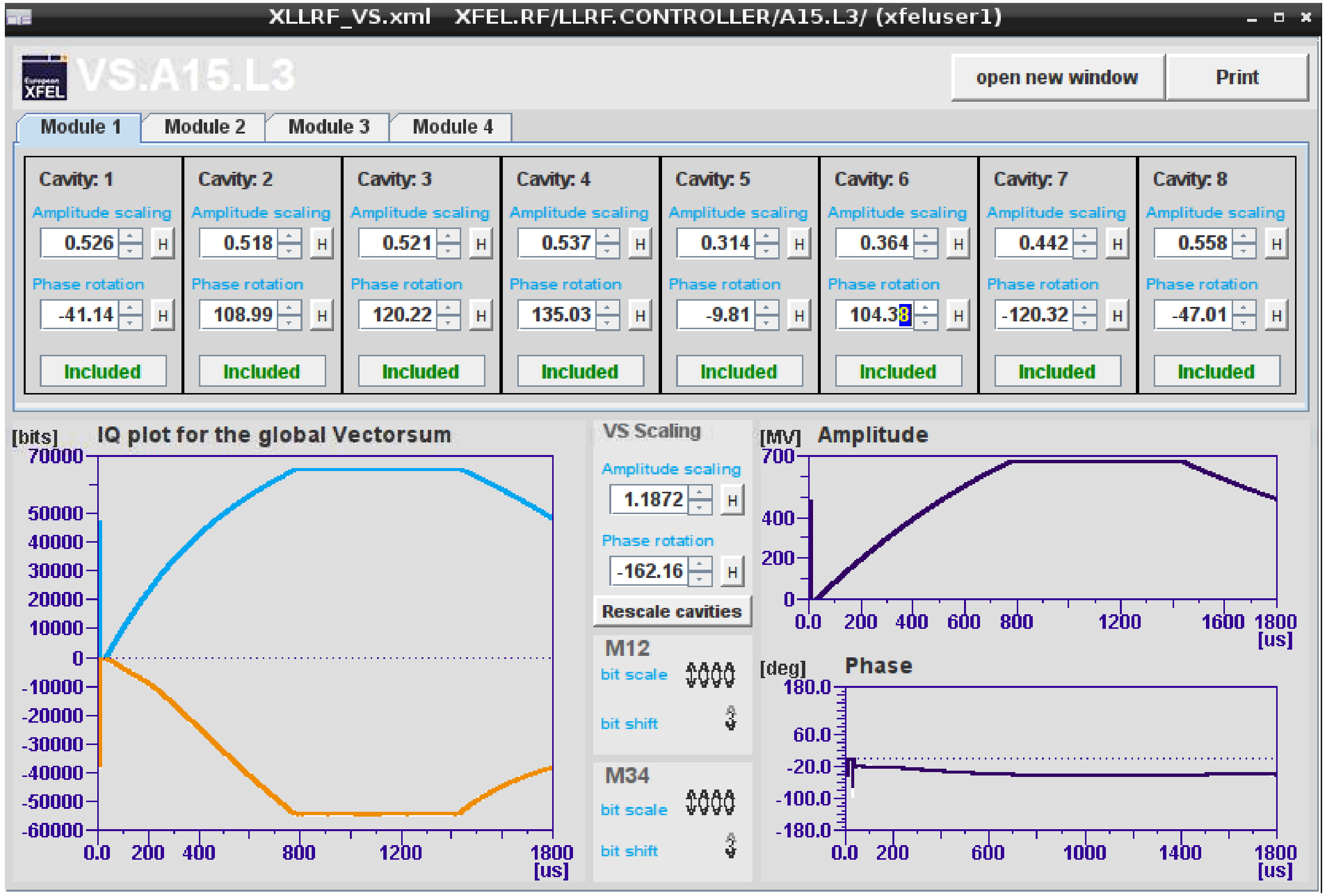
Final fit,
bcal=-3.441 +i*0.4138

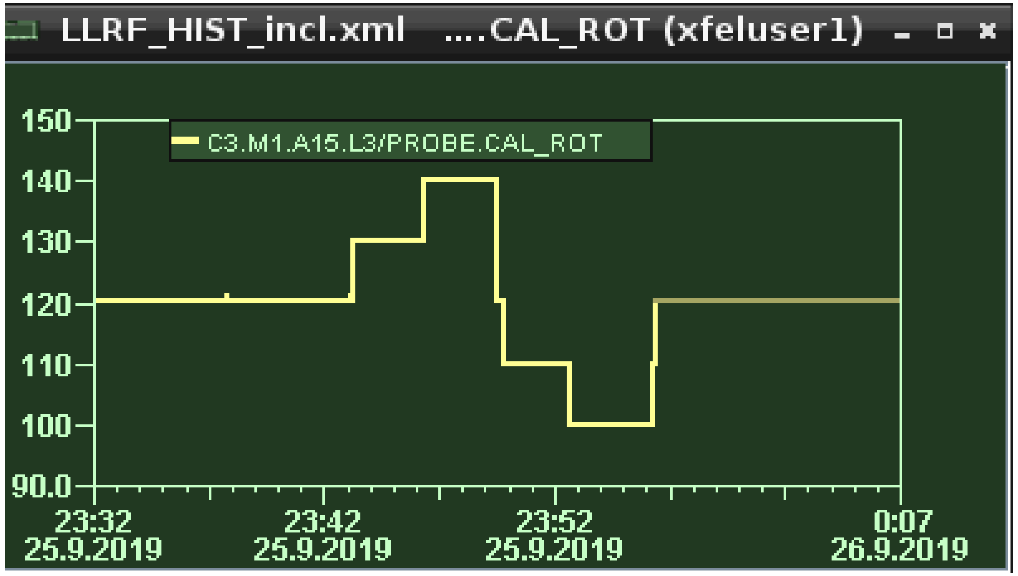


Results

C3.A15 @ 680 MV
0.55 mA
(1015 bunches@ 0.25 nC)

Calibration of the C3.M1.A15.L3 was changed in amplitude and in phase.
The scan range was ±20 deg. in phase and ±4% in amplitude respectively.





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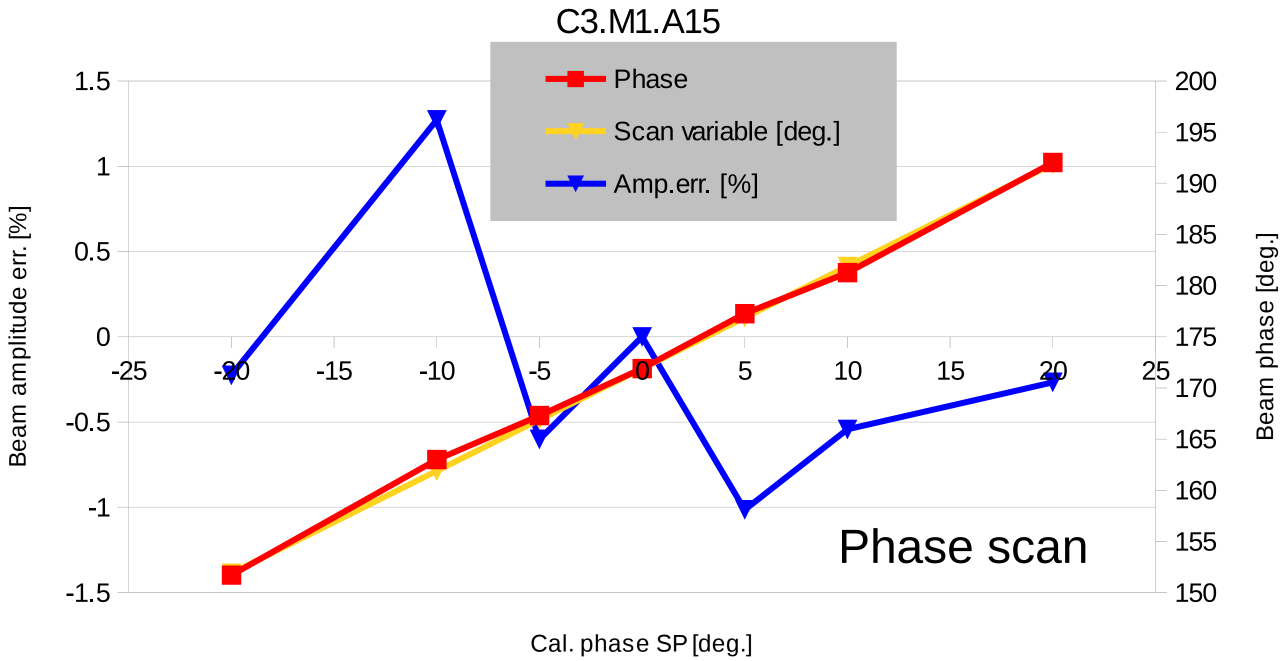
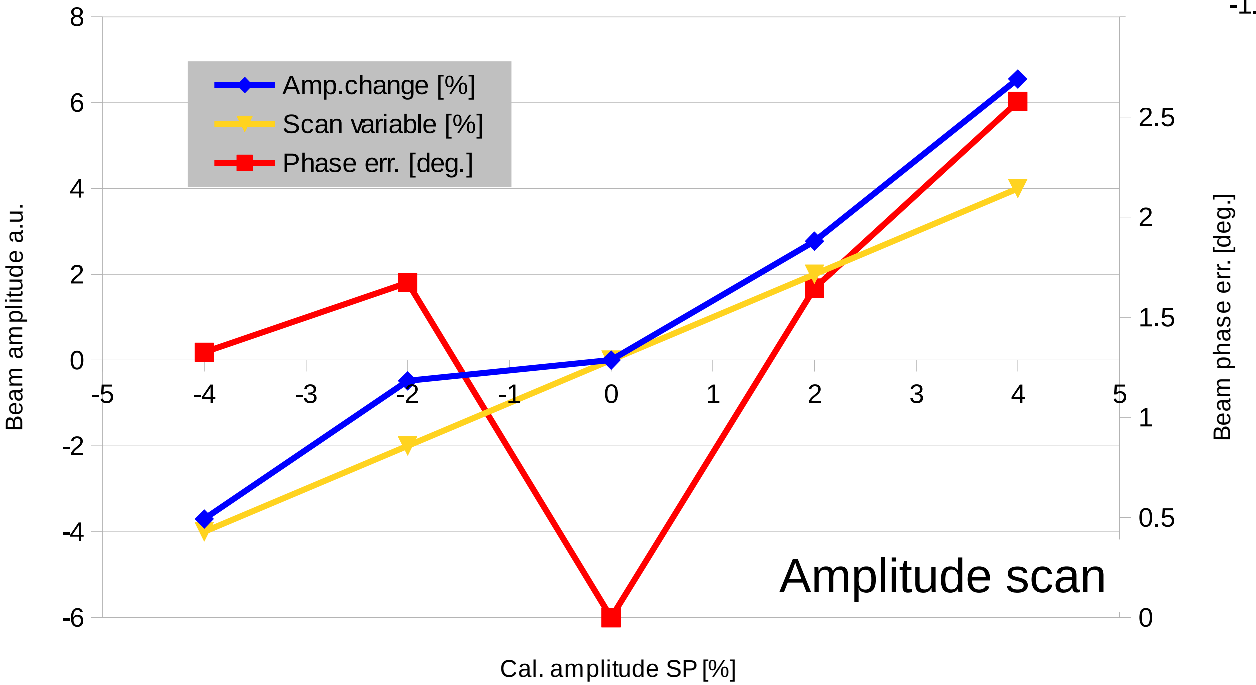


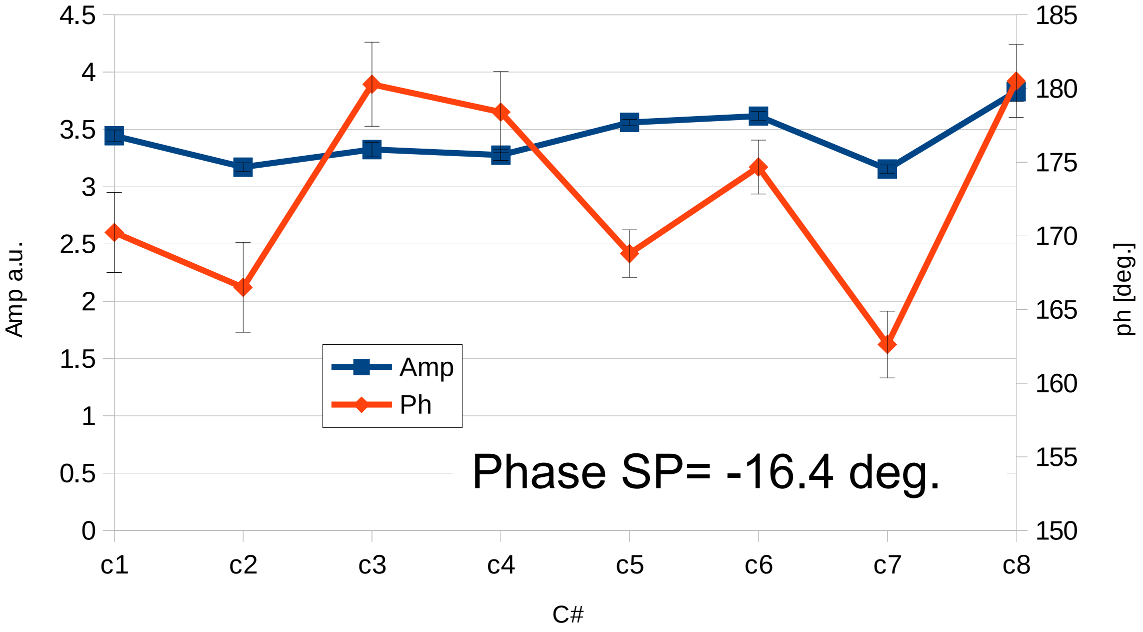


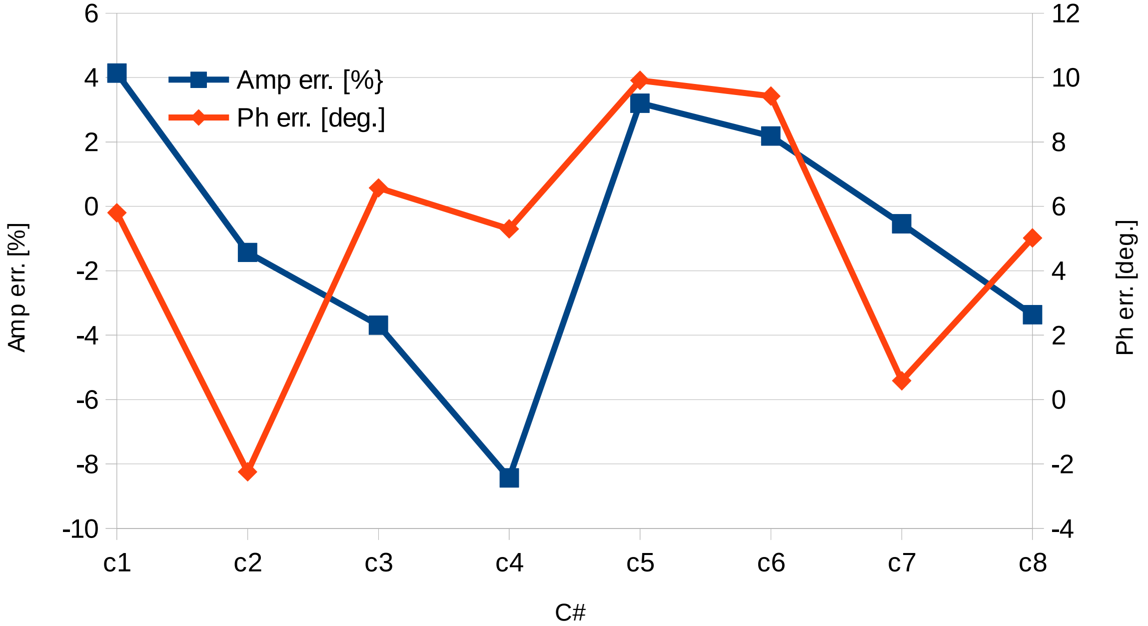
Calibration of the C3.M1.A15.L3 was changed in amplitude and in phase.
The scan range was ±20 deg. In phase and ±4% in amplitude respectively versus the nominal settings.

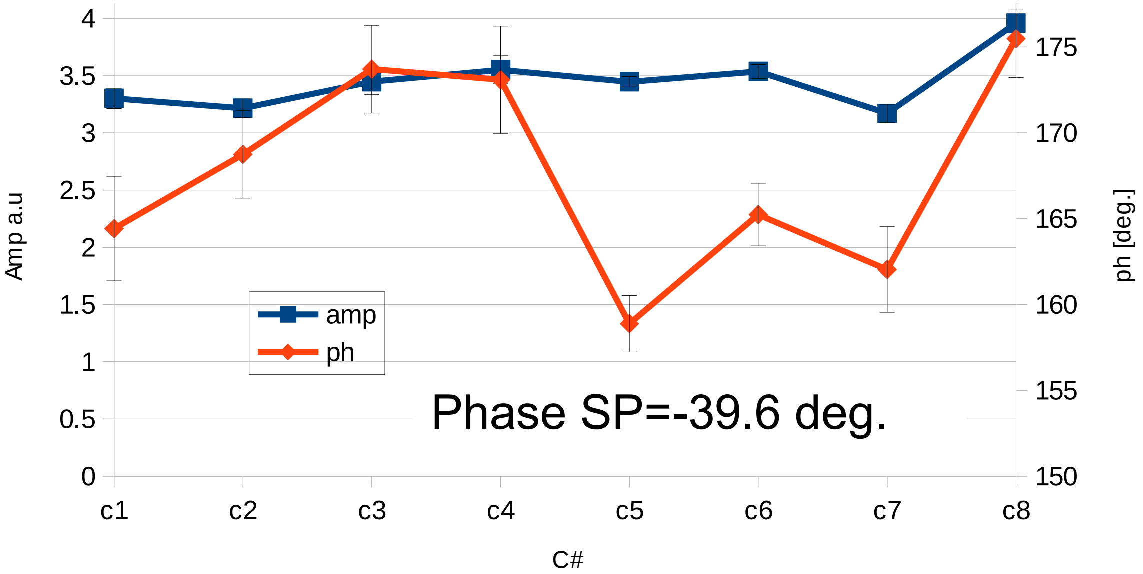
Results (1)

A15 @ 680 MV
0.55 mA
(1015 bunches@ 0.25 nC)

- Measurements done with 2 different phase SP, both measurements separated by 2 days.
- Beam phase shifted by few deg. in all cavities while it should stay unchanged.
- Requires more investigations.







Conclusion

- Proposed method can be used transparently to machine operation.
- The currently achieved accuracy is probably 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.
- Possible error sources are: cross-talks between RF signals, nonlinear effects, errors in RF signal calibration. Unclear is the presence of ~9kHz oscillations at detuning during beam time. It comes from probe phase derivative. Without signal filtering it is hardly visible. It is more visible when the RF pulses are averaged.
- There are still areas for further improvements that possibly increase accuracy (e.g. better modeling of beam induced voltage, better detuning approximation).
- The proposed method is CPU hungry. Application of parallel computation will speed up the operation. For single RF station 32 threads (or CPU cores) are needed. It was not tested but application of GPU would be the perfect hardware platform.

Thank you

Contact

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