ATF

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"Laser-Compton X-Ray generation stabilization at KEK LUCX facility by Digital LLRF phase&amplitude feedforward implementation into RF system"

POPOV Konstantin
ARYSHEV Alexander
TERUNUMA Nobuhiro

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ATF

1. **Introduction into KEK LUCX facility and research motivation;**
2. **Digital Low-Level Radio Frequency feedforward implementation technique;**
3. **Developed signal processing and feedforward algorithm;**
4. **Experiments performed at KEK LUCX facility;**
5. **Summary and conclusion**

Laser-Compton X-Ray generation experiment at KEK LUCX facility

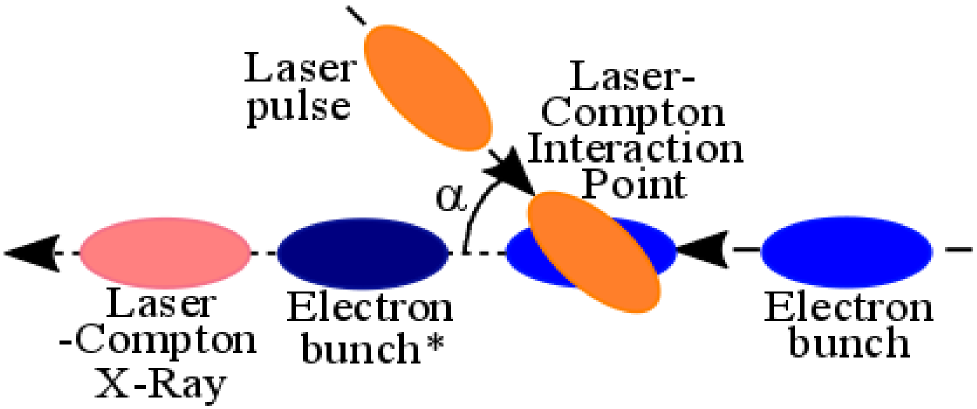


Figure 1: Laser-Compton backscattering geometry schematics

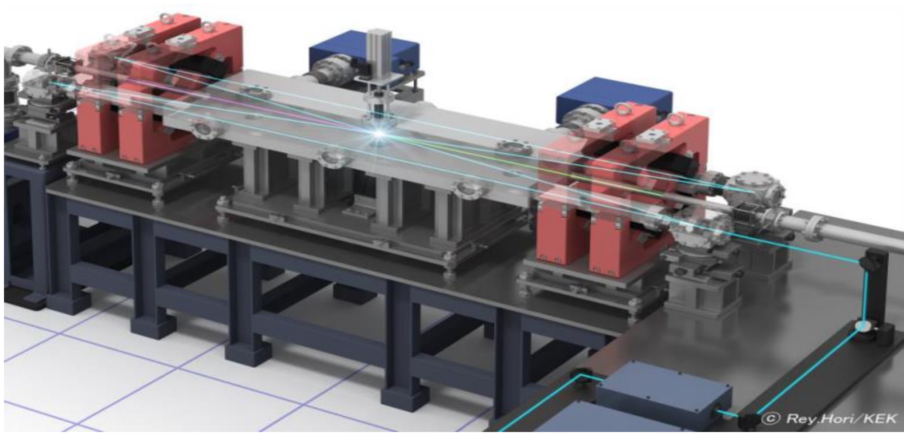


Figure 2: Schematics of the Laser-Compton X-Ray generation at KEK LUCX facility

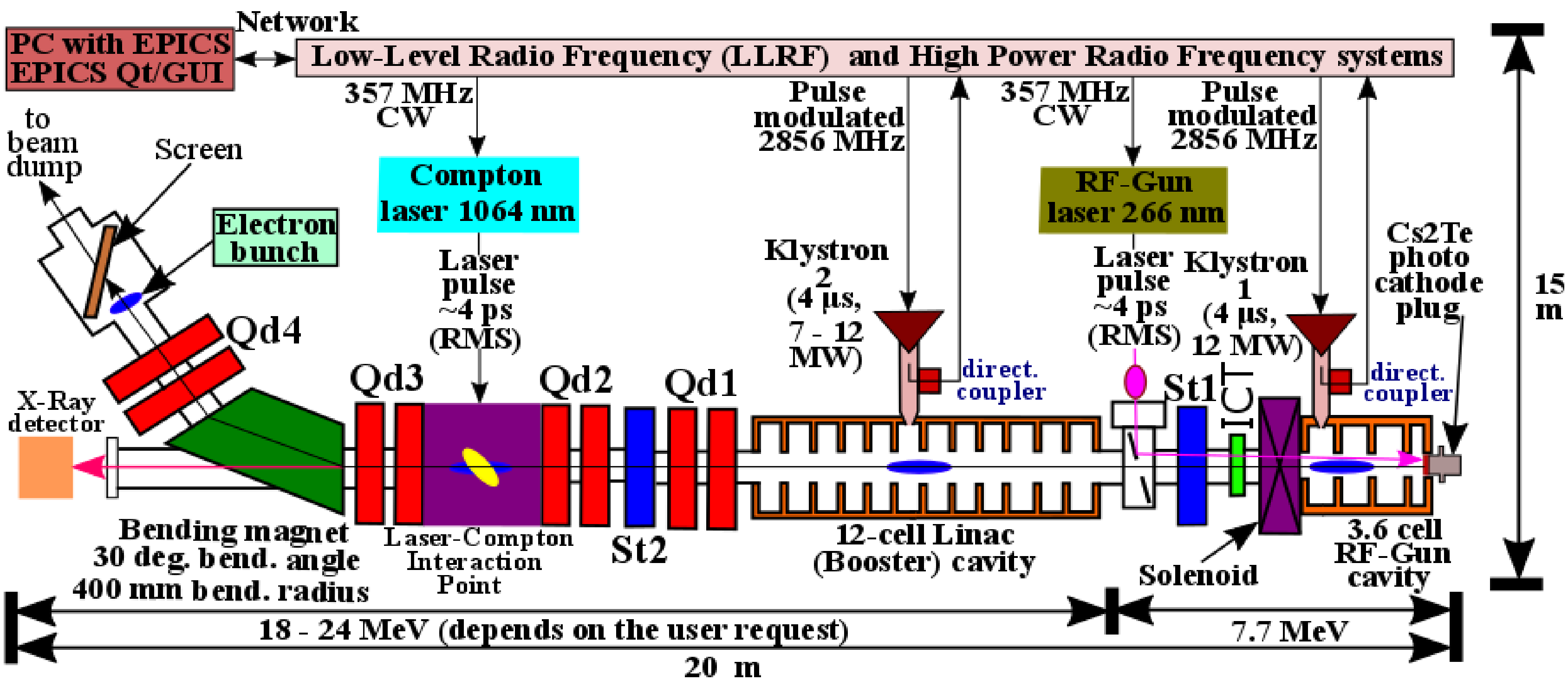
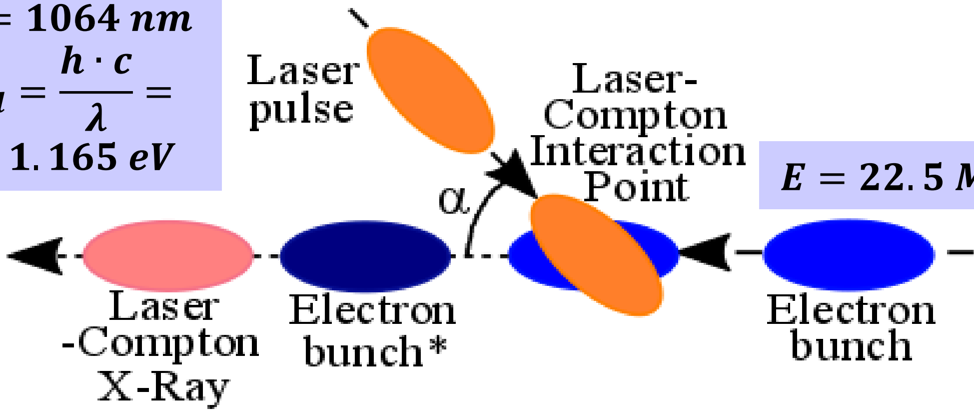


Figure 3: KEK LUCX facility beamline schematic: **Qd** is the quadrupole doublet, **St** is the steering magnet

Research motivation

$$\lambda = 1064\ nm$$
$$E_l = \frac{h \cdot c}{\lambda} = 1.165\ eV$$



$$E = 22.5\ MeV$$

Figure 4: Laser-Compton backscattering geometry schematics

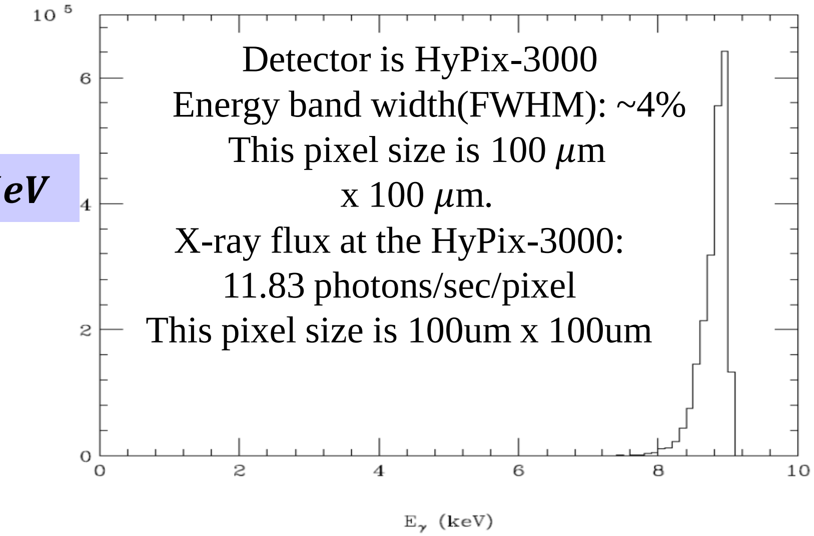


Figure 5: X-Ray energy distribution calculated at the X-Ray Detector location in CAIN (calculated by K. Sakaue and Y. Koshiba)

Laser-Compton X-Ray bandwidth:

$$\frac{dE_\gamma}{E_\gamma} \approx \sqrt{\left(\frac{\varepsilon_n}{\sigma_x}\right)^4 + 4 \cdot \left(\frac{dE}{E}\right)^2}$$

X-Ray energy:

$$E_\gamma = 4 \cdot \gamma^2 \cdot E_l$$
$$E_\gamma = 9\ keV$$

Motivation:

Stable accelerating field = stable beam parameters = stable laser-Compton X-Ray source at KEK LUCX facility

Goal:

Develop, implement and test a digital Low-Level Radio Frequency (LLRF) feedforward for precise control of RF field at KEK LUCX facility

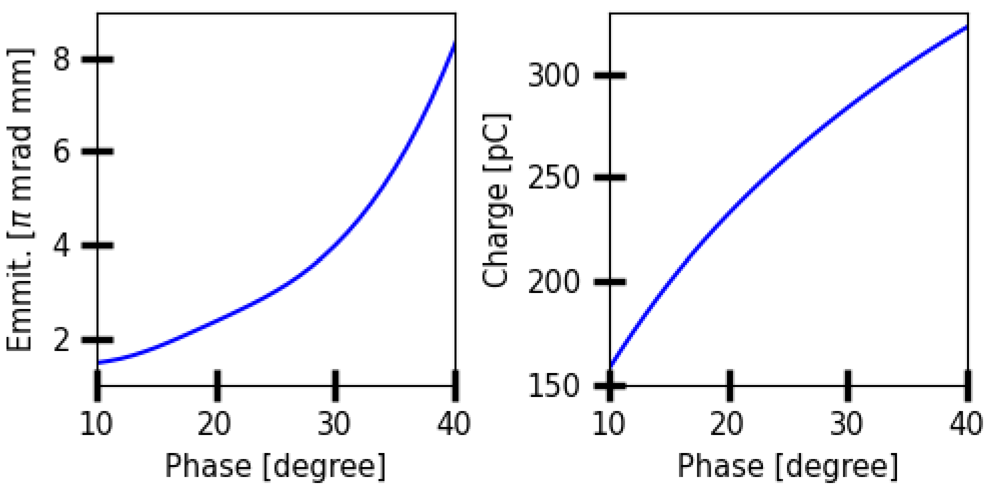


Figure 6: Bunch parameters: (a) is the norm. trans. emittance vs RF-Gun phase, (b) is the bunch charge vs RF-Gun phase

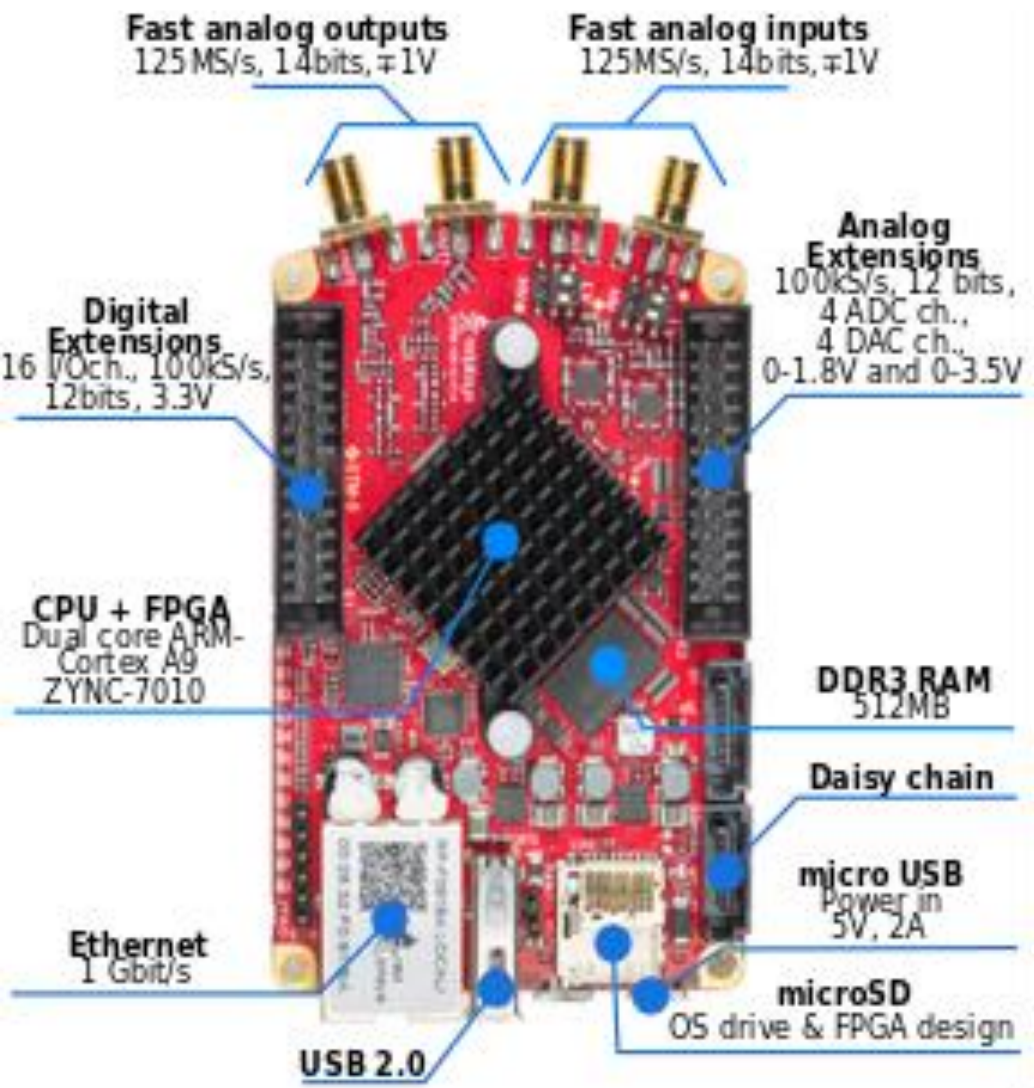


Figure 7: RedPitaya STEMlab 125-14 FPGA board

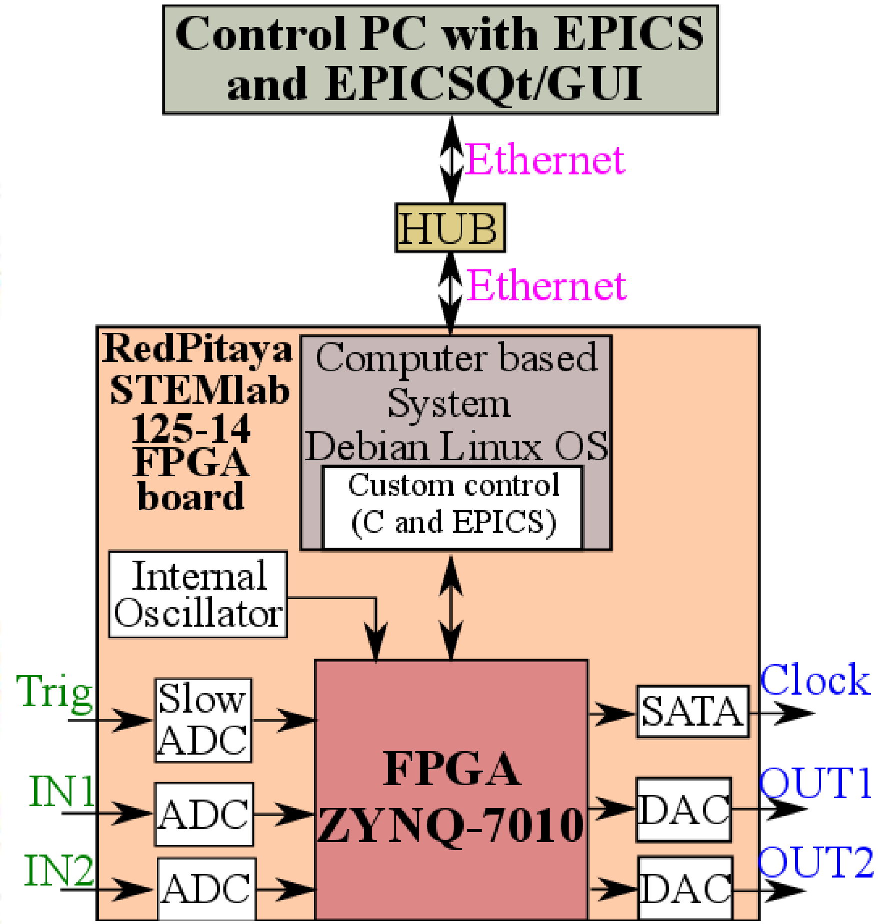


Figure 8: Schematic of single RedPitaya STEMlab 125-14 FPGA board communication logic with PC

Digital Down Conversion (DDC)&Digital Up Conversion (DUC) technique

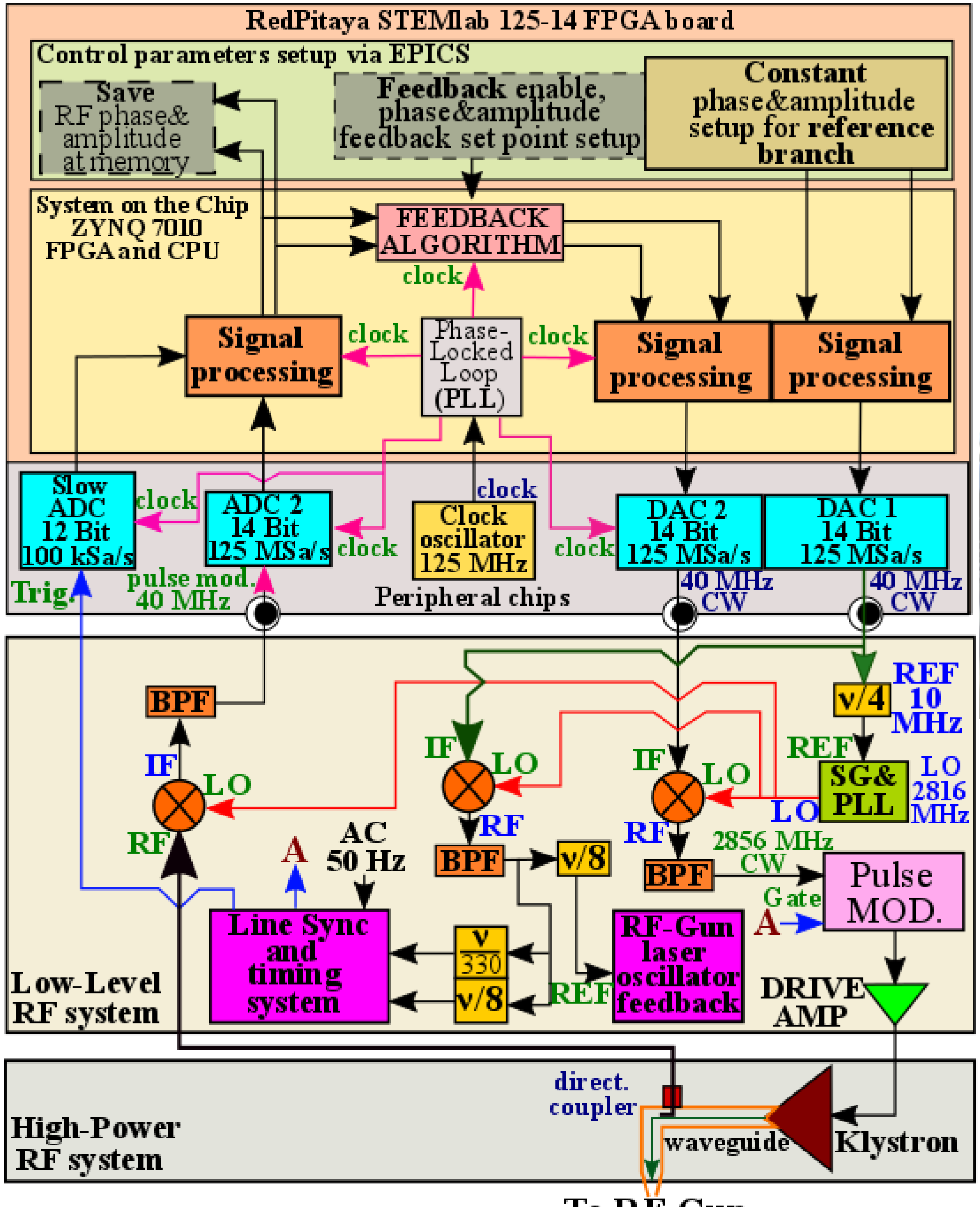


Figure 9: Schematic of DDC&DUC technique implementation into LLRF system

Figure 10: Frequency divider (1/4)

Figure 11: 10 MHz REF Input (example)

Figure 12: RF-Mixer: Mini-circuits ZFM-4212+

Figure 13: 2856 MHz Band Pass Filter photo

Figure 14: 40 MHz Band-Pass Filter

RF-Gun accelerating field waveform

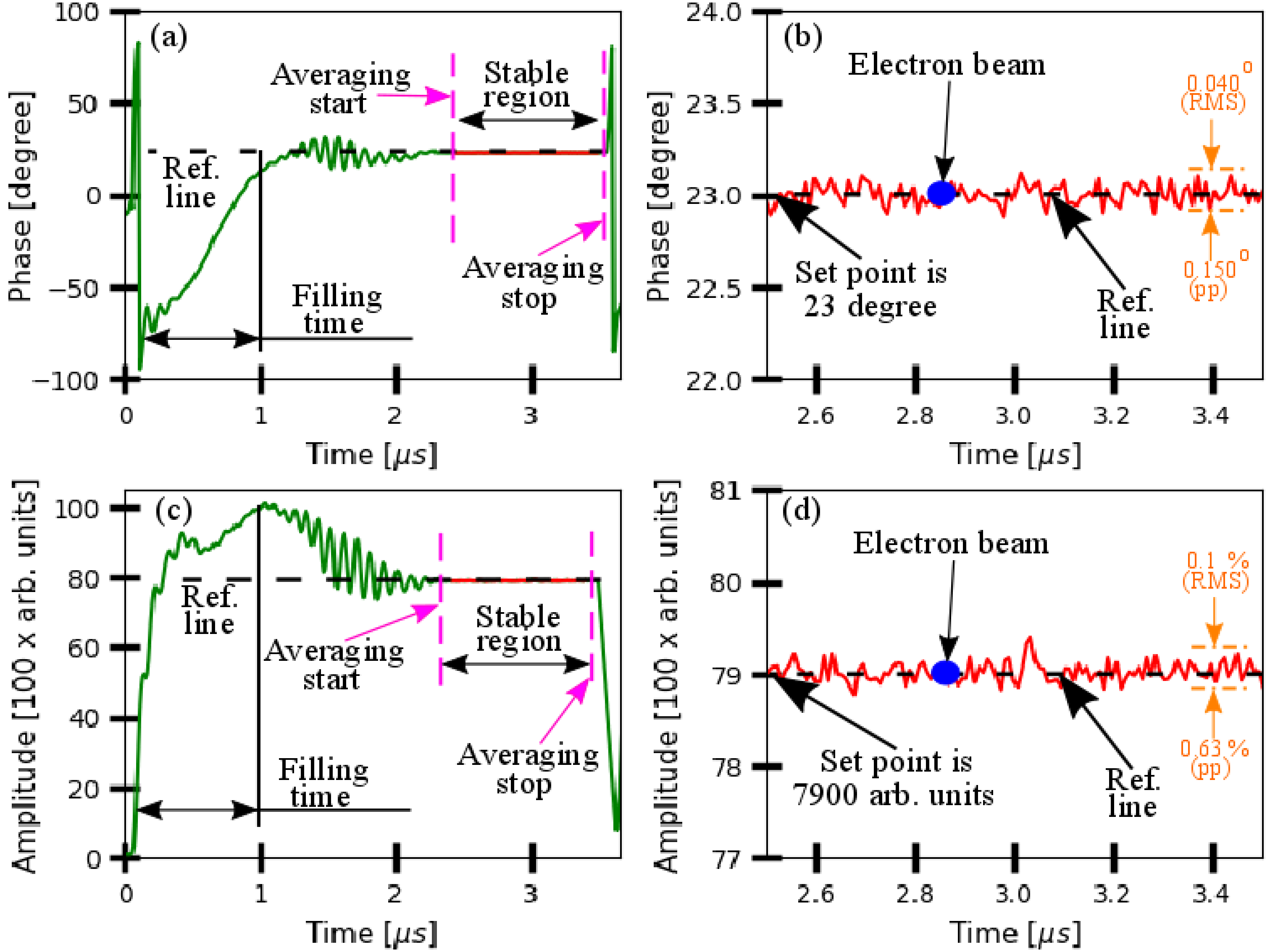


Figure 15: RF-Gun RF field waveform: **(a)** and **(b)** are RF-Gun accelerating field phase and zoomed in stable region of the phase, **(c)** and **(d)** are RF-Gun accelerating field amplitude and zoomed in stable region of the amplitude

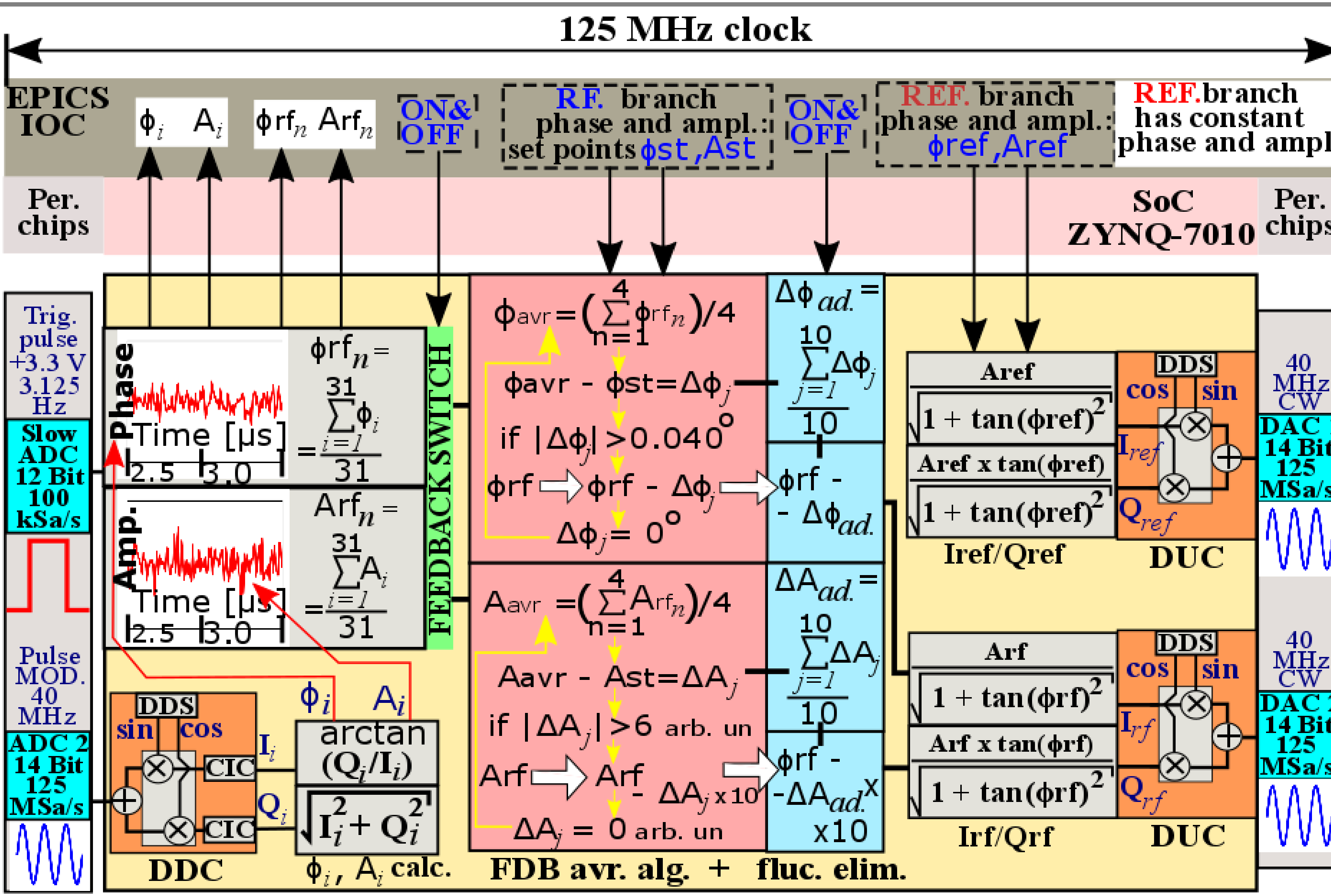


Figure 16: Block diagramm of the signal processing and feedforward algorithm implemented into the RedPitaya STEMlab 125-15 FPGA board

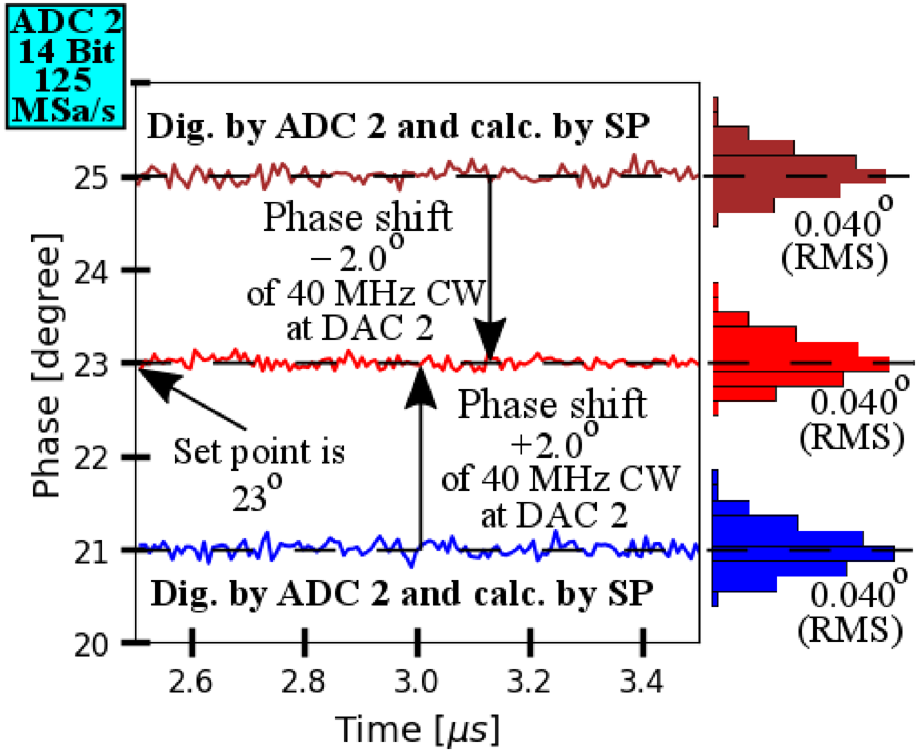


Figure 17: Phase correction illustration

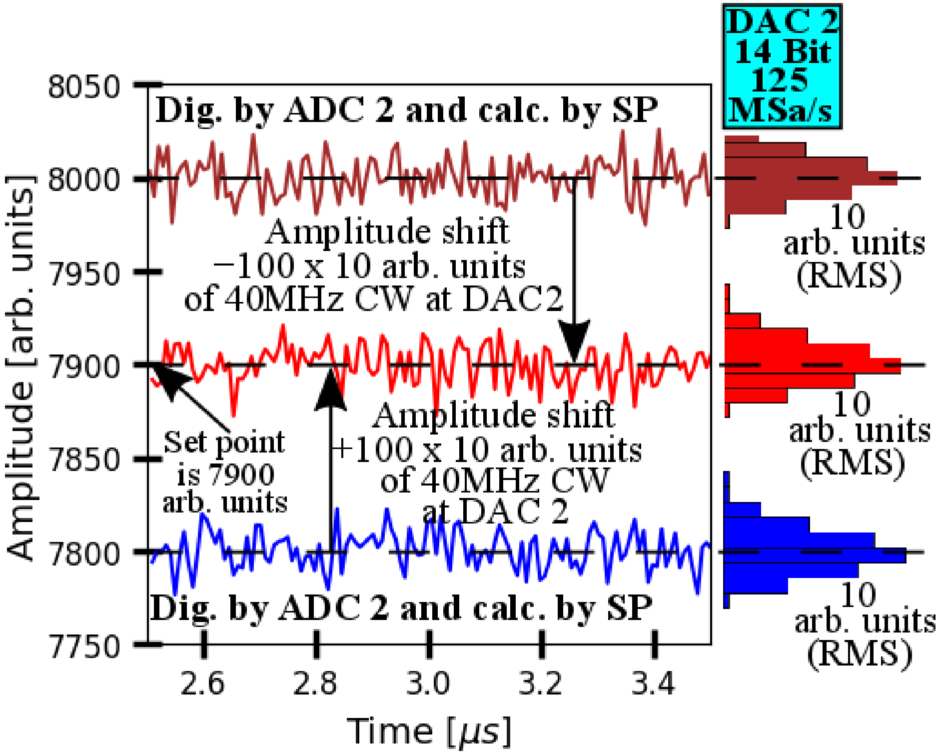


Figure 18: Amplitude correction illustration

Experimental setup (RF-Gun cavity)

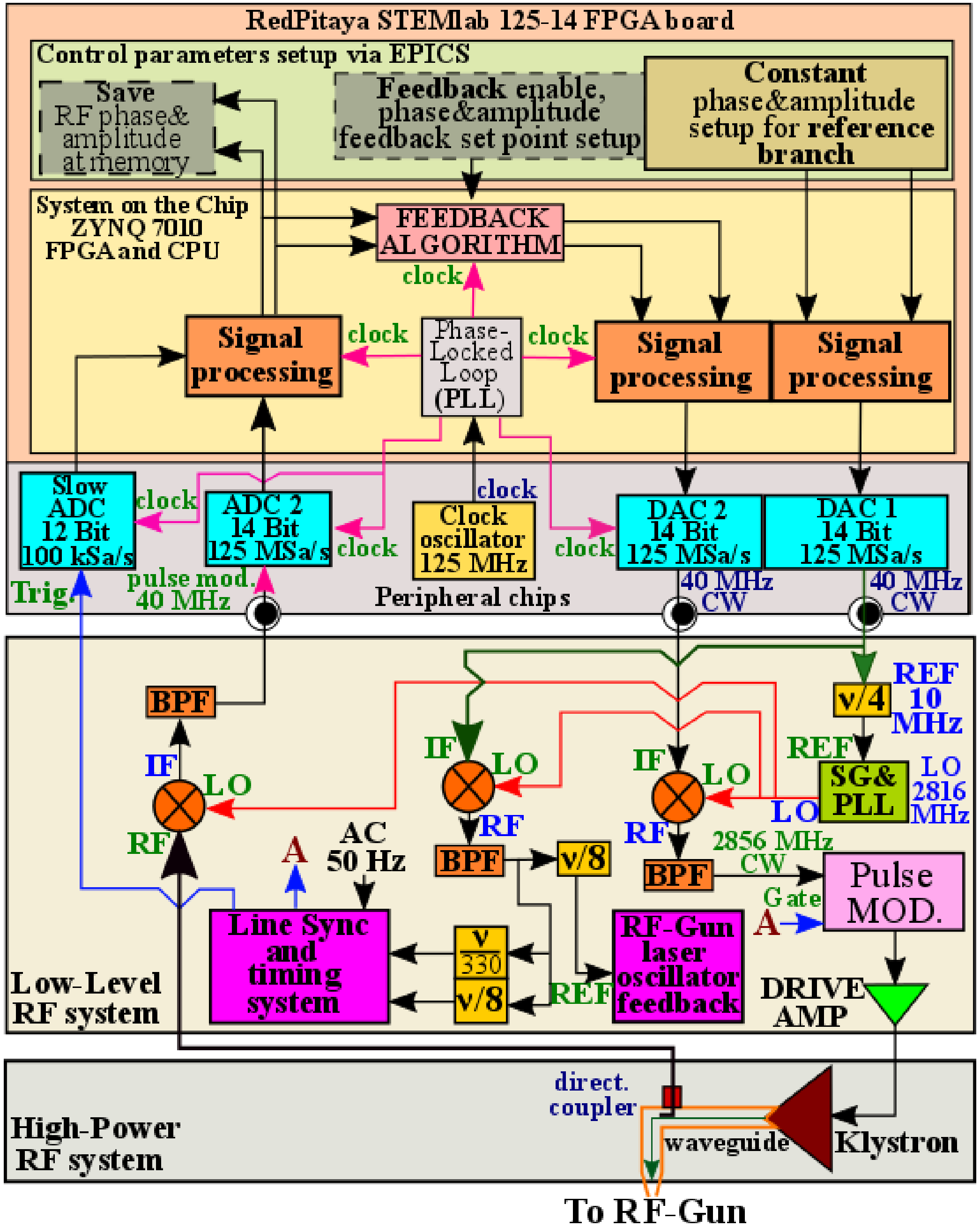


Figure 19: Experimental setup of the feedback performance for the RF-Gun cavity

Figure 20: Keysight E5052B SSA

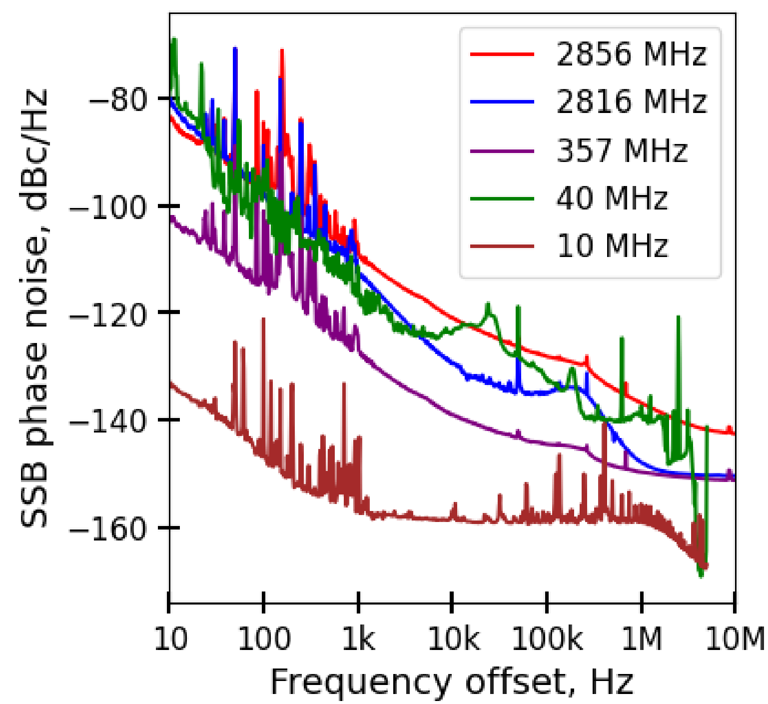


Figure 21: CW signals phase noise map

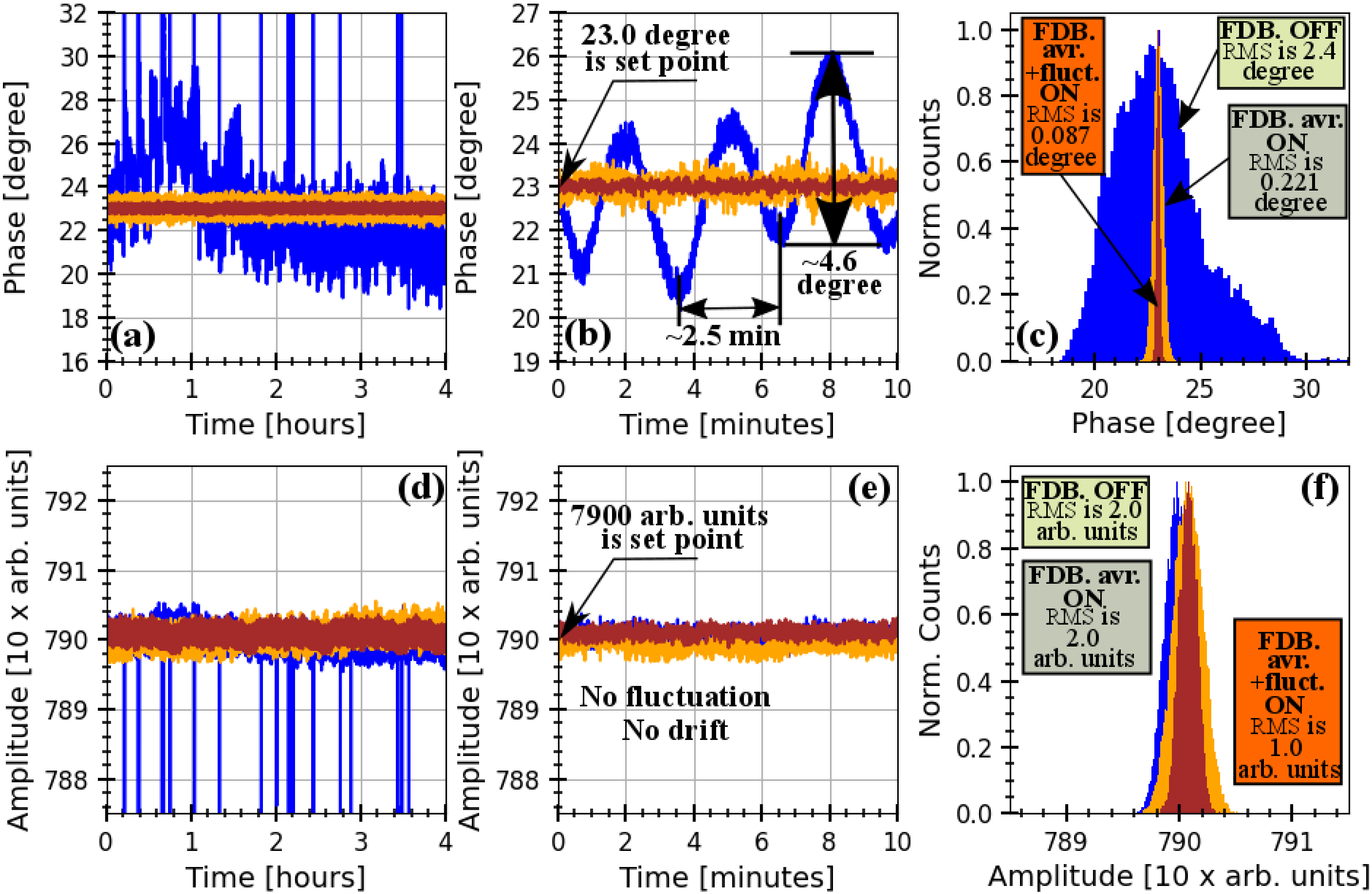


Figure 22: RF-Gun accelerating field stability experimental data (blue line is **FDB OFF**, orange line is **FDB avr. ON**, red line is **FDB avr. + fluct. elim ON**): (a), (b) and (c) are RF-Gun phase stability during 4 hours, first 10 minutes and histogram; (d), (e) and (f) are RF-Gun phase stability during 4 hours, first 10 minutes and histogram

Experiment with electron beam: setup

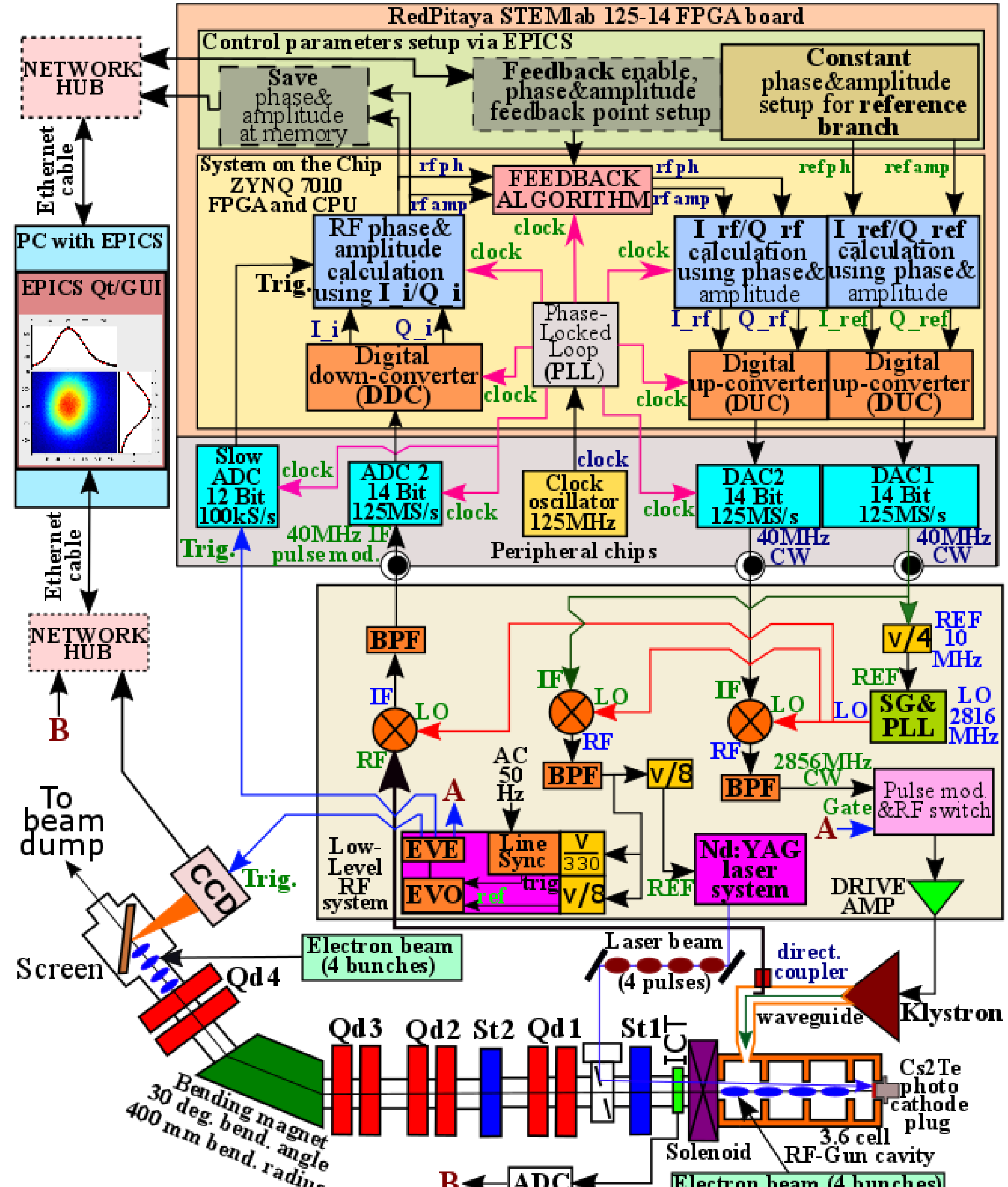


Figure 23: Experimental setup

***E* is 7.7 MeV**

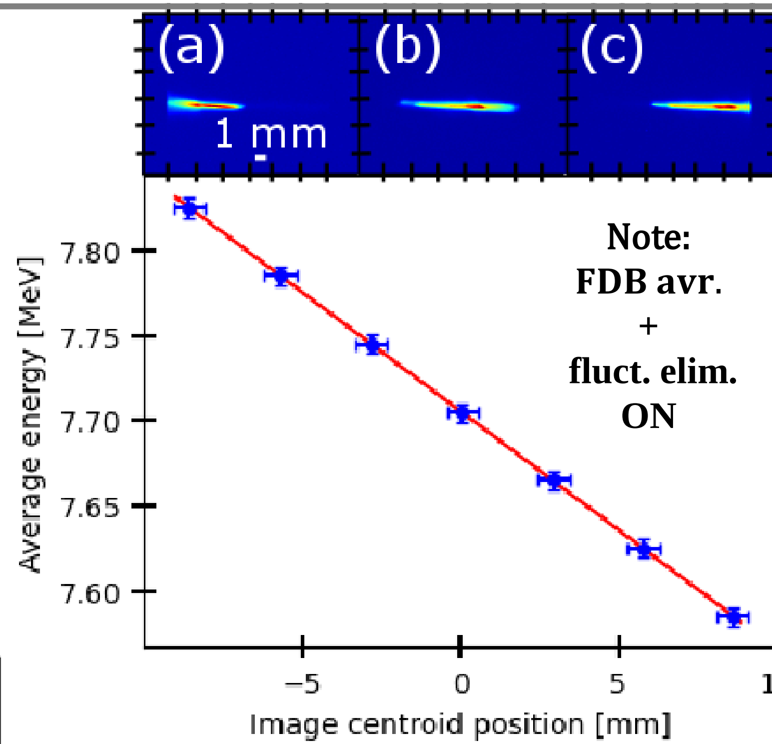


Figure 24: Average energy vs image centroid position calibration curve (blue dots is exp. data and redline is linear fit)

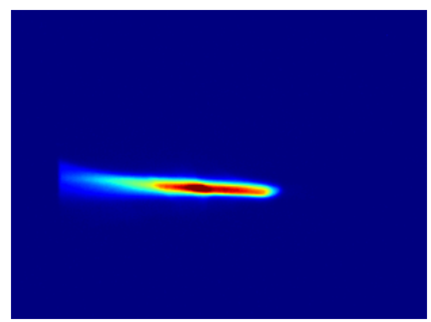


Figure 25: Typical image on screen measured by CCD

η_x is 590 mm

1. Detect image

2. Fit with Gauss

3. Calculate horizontal dispersion at screen loc.

4. Use eq. 1

$$\Delta E = \Delta x \cdot E/\eta_x \quad (1)$$

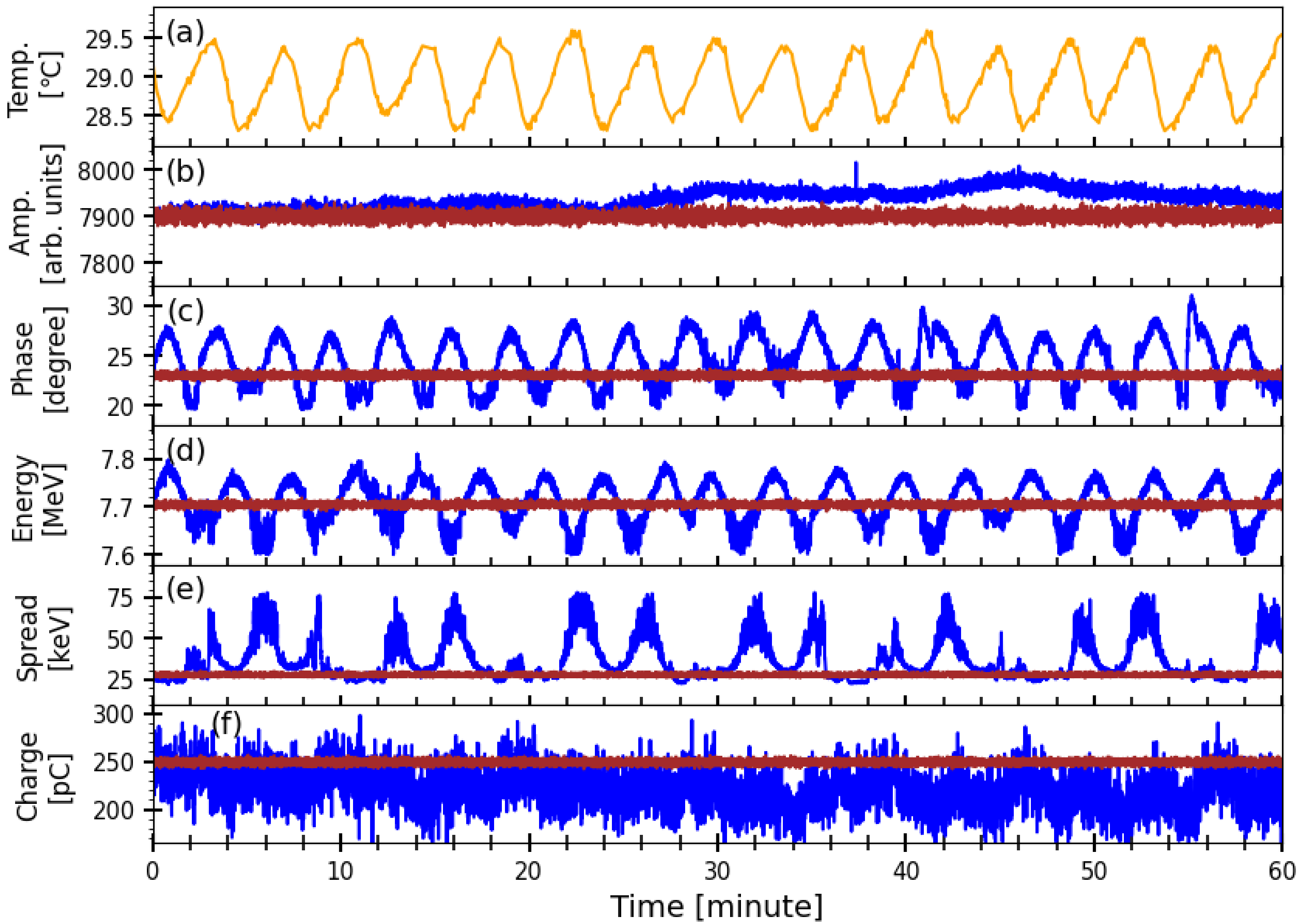


Figure 26: Experimental data (blue line is **FDB. OFF** and red line is **FDB avr.+ fluct. elim. ON**): (a) is the cavity surface temperature, (b) is the field amplitude, (c) is the field phase, (d) is the average energy, (e) is the energy spread, (f) is the bunch charge vs time

Experiment with electron beam: results

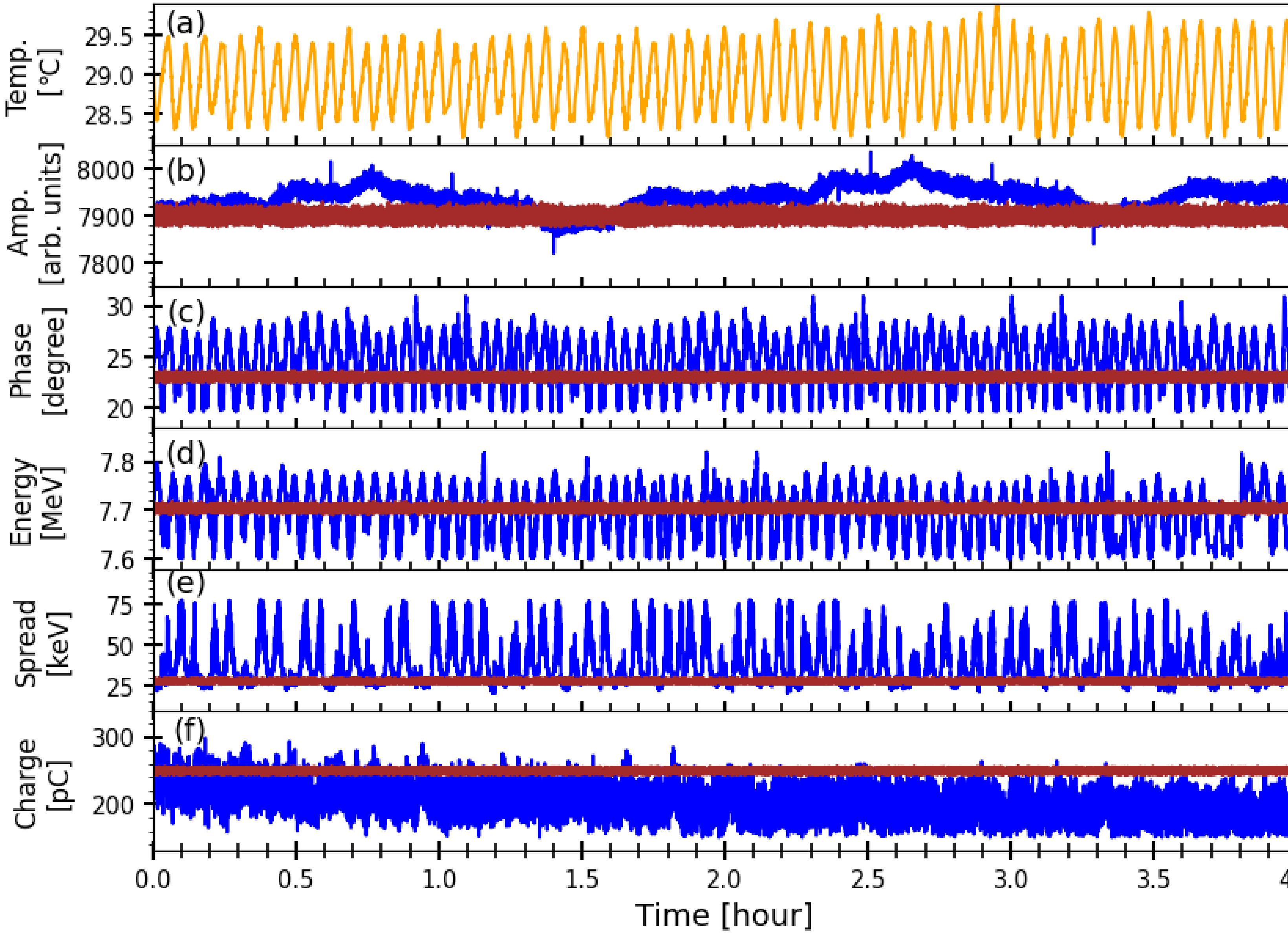


Figure 27: Experimental data (blue line is **FDB. OFF** and red line is **FDB avr.+ fluct. elim. ON**): (a) is the cavity surface temperature, (b) is the field amplitude, (c) is the field phase, (d) is the average energy, (e) is the energy spread, (f) is the bunch charge vs time

Experiment with electron beam: histograms

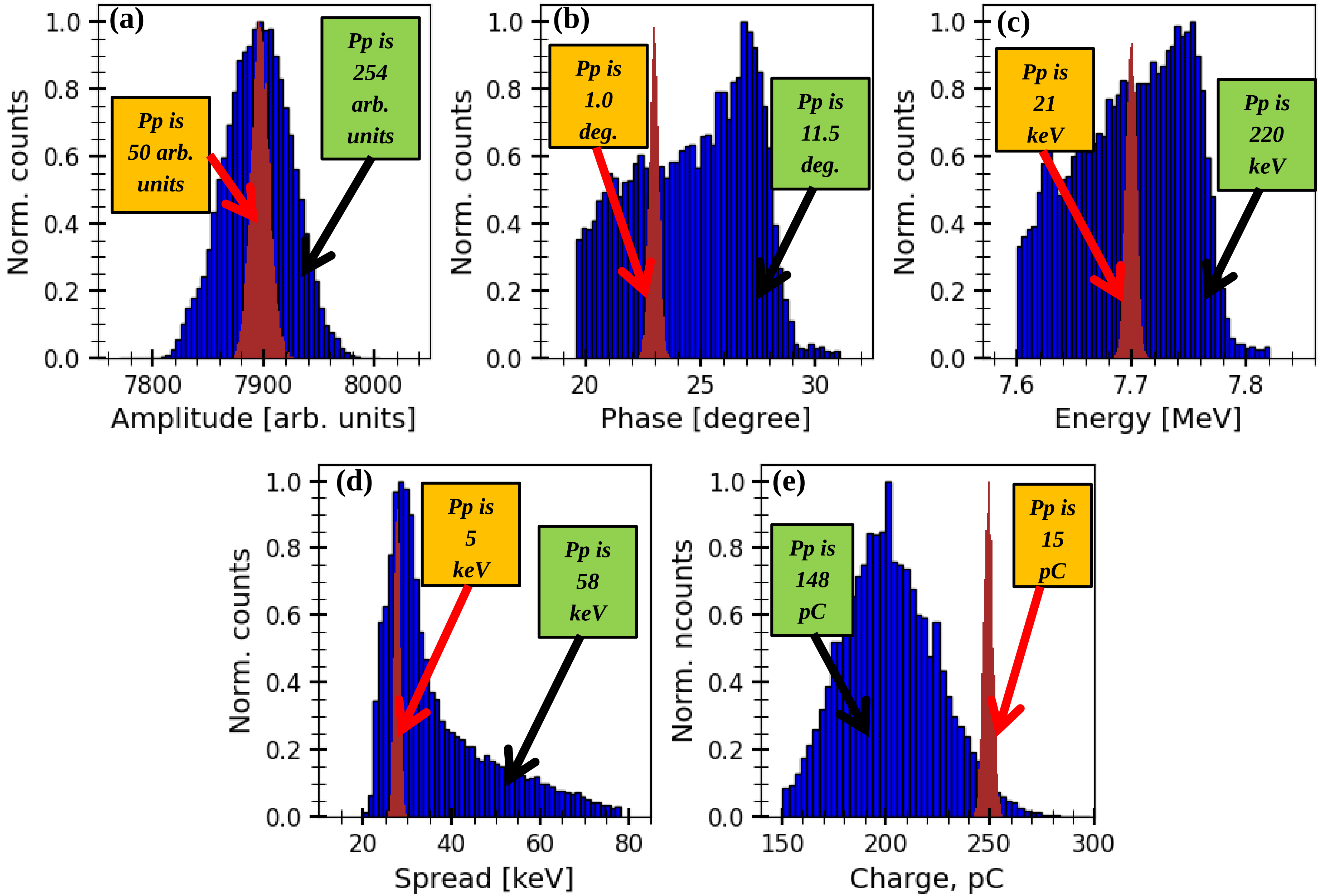


Figure 28: Experimental data (**blue histogram** is **FDB. OFF** and **red histogram** is **FDB. avr + fluct. elim. ON**): (a) is the field amplitude, (b) is the field phase, (c) is the average energy, (d) is the energy spread, (e) is the bunch charge

Summary and conclusion

Table 1: Summary

Parameter	Value	Peak-to-peak stability with FDB. OFF	Peak-to-peak stability with FDB. avr. + fluct. elim. ON	OFF / ON
RF-Gun accelerating field amplitude, arb. units	**7900**	**254**	**50**	**5**
RF-Gun accelerating field phase, degree	**23**	**11.5**	**1**	**11.5**
Average energy, MeV	**7.7**	**0.220**	**0.021**	**10.5**
Energy spread (RMS), keV	**25**	**58**	**5**	**11.6**
Bunch charge, pC	**250**	**148**	**15**	**10.0**

Conclusion:

Digital Low-Level Radio Frequency Feedforward based on RedPitaya STEMlab 125-14 FPGA board was developed, implemented and tested at KEK LUCX facility. The phase and amplitude were stabilized 11.5 times and 5 times, respectively. As a result, beam average energy, energy spread and bunch charge stability was improved 10 times. As an optimistic prediction, laser-Compton X-Ray characteristics stability will be improved 10 times too.


THANK YOU FOR
ATTENTION!

Electron beam parameters jitter influence on Compton X-ray photons parameters

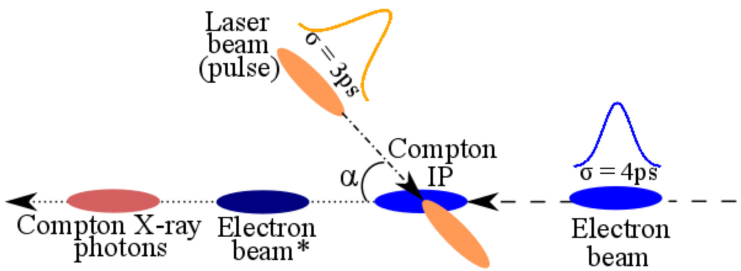


Figure Bc.1.: Inverse Compton scattering phenomena.

Bad synchronization case. It means, feedforward is turned OFF

Compton laser pulse (RMS) length at IP is equal to 3 ps. **Electron beam arrival time jitter is 1.1ps, while the bunch length is 4ps. So, 27.5% the bunch charge is lost** because of time arrival jitter of electron bunch => **Compton photons intensity is quarter less because of time arrival jitter of electron bunch.**

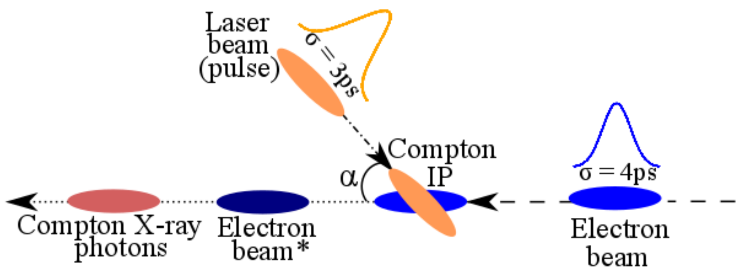


Figure Bc.2.: Inverse Compton scattering phenomena.

Good synchronization case. It means, feedforward is turned ON

Compton laser pulse (RMS) length at IP is equal to 3 ps. **Electron beam arrival time jitter is 100fs , while the bunch length is 4ps. As a conclusion, 3% of the bunch charge is lost** because of time arrival jitter of electron bunch => **Compton photons intensity is close to the ideal case.**