氏　　名	Popov Konstantin
学位(専攻分野)	博士(理学)
学 位 記 番 号	総研大甲第 2445 号
学位授与の日付	2023 年 9 月 28 日
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学 位 論 文 題 目	Digital Low-Level Radio-Frequency phase-amplitude feedback development and its application for KEK LUCX facility stabilization
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Summary of Doctoral Thesis

Full name: Popov Konstantin

Title: “Digital Low-Level Radio-Frequency phase-amplitude feedback development and its application for KEK LUCX facility stabilization”

KEK LUCX facility is linear accelerator technology and beam instrumentation R&D test-bench for ILC, KEK ATF and any other present and future accelerators at KEK (High Energy Accelerator Research Organization, Japan) and across the world. The facility is a compact normal-conductive multi-bunch electron accelerator. It has laser-driven photocathode RF-Gun and 12-cell Linac. Both cavities are standing wave cavities. LUCX accelerator is pulse facility. The electron beam generation repetition rate is 3.125Hz. Control system of the facility includes hardware and software. Hardware side consists on timing, Low-Level RF systems, interlocks and DAQ. Software side includes EPICS server-client parts, software interlocks and graphical user interfaces. KEK LUCX facility has all necessary equipment and infrastructure to carry Low-Level RF phase and amplitude feedback study.

The Ph.D. research had two motivations: global and technical. In accelerator science, high brightness modern particle injectors and compact linear light sources (X-Ray and THz) require stable RF-Gun and accelerating cavities RF-field phase and amplitude to achieve stable pulse-by-pulse electron beam parameters: emittance, charge, average energy, energy spread (RMS), bunch arrival time, bunch length (RMS) etc. The common practice to stabilize the RF-field phase and amplitude is a Low-Level RF feedback implementation into the facility control system. Recently, the FPGA boards based on System-on-Chip technology (FPGA plus CPU) became commercially available, which made digital Low-Level Radio-Frequency phase-amplitude feedback field is a hot topic at the accelerator science and beam instrumentation community. The commercially available FPGA boards with 100MSa/s sampling rate ADC and DAC chips is ultimate tool from the shelf.

However, these boards have several limitations. The implementation of the boards into LLRF system must be comprehensively investigated. This research investigates implementation of the FPGA board based Low-Level RF feedback to stabilize accelerating field phase and amplitude inside the LUCX S-band RF-Gun and 12-cell Linac. RedPitaya STEMlab 125-14 FPGA board equipped with ZYNQ-7010 chip was chosen for the feedback development, implementation and test at KEK LUCX facility.

The FPGA board is a standalone commercially available module with FPGA chip programming flexibility. Also, it has competitive specifications with other commonly used FPGA based systems.

The technical motivation is narrower than global motivation. KEK LUCX facility did not have LLRF phase&amplitude monitor (stability diagnostics) and the feedback for RF-Gun and 12-cell Linac (main accelerating cavity). The accelerator could not operate stable more than 40 minutes due to the accelerating field phase and amplitude drift, fluctuation and jitter. Also, it had high discharges rate and RF system fails. So, the accelerating field phase and amplitude stabilization was vital for the facility to research the compact monochromatic X-Ray source, coherent THz radiation source and new beam instrumentation techniques.

The following tasks were accomplished during the Ph.D. research:

- Review the basic accelerator feedback principles possible to utilize with RedPitaya STEMlab 125-14 FPGA board.
- Review the stability and reliability of existing KEK LUCX facility beam diagnostics, DAQ, timing and LLRF.
- Creation of an ASTRA particle tracking simulation for LUCX beamline. The electron beam parameters dependence on the RF-Gun and 12-cell Linac accelerating fields phase simulation in ASTRA tracking code. Beam line simulation model limitations study and its potential usage for feedback corrections calculation.
- Implementation of running averaging feedback algorithm with the digital In-Phase and Quadrature demodulation&modulation on the RedPitaya STEMlab 125-14 FPGA board.
- Summary of beam parameters, tuning knobs with associated tuning ranges which can be included into feedback algorithm.

• FPGA based LLRF feedback programming and its implementation into KEK LUCX facility LLRF system.

• Inclusion of the feedback system tuning knobs and monitors into the existing EPICS control system of LUCX.

• Demonstration of the accelerating field phase and amplitude stability in the LUCX S-band RF Gun and 12-cell Linac. Long-term measurement of the feedback system performance. The electron beam energy, energy spread, charge stability measurement.

The Ph.D. research presents results of the RedPitaya STEMlab 125-14 FPGA board based LLRF phase and amplitude feedback development, implementation and test at the KEK LUCX facility. The RF-Gun and 12-cell Linac cavities accelerating field phases stability was improved from 2.4° (RMS) to the 0.09° (RMS). The experimental results of the electron beam parameters stabilization (average energy, energy spread (RMS) and bunch charge) demonstrate 10 times improvement.

（別紙１ Separate Sheet 1）

Results of the doctoral thesis defense

博士論文審査結果

Name in Full
氏　　名 Popov Konstantin

Title
論文題目 Digital Low-Level Radio-Frequency phase-amplitude feedback development and its application for KEK LUCX facility stabilization

本研究は、KEK 小型電子加速器（LUCX: Laser Undulator Compact X-ray source）にデジタル低電力高周波(LLRF)フィードバックシステムを導入し RF の位相・振幅の安定化に貢献するものである。LUCX では 2856 MHz、幅 4 μs の RF パルスを RF 電子銃と定在波型の常伝導加速空洞に供給してビームを生成・加速、レーザー逆コンプトン散乱 X 線光源の開発が行われてきた。Popov Konstantin 氏は、ADC と DAC を搭載した汎用の SoC(System on Chip) FPGA ボードを使用し、RF のフィードバック制御と FPGA ボード間やレーザーとの同期に関しての検討を行い、システムの構築をおこなった。また、制御のために加速器制御に使用される EPICS（Experimental Physics and Industrial Control System）の組み込みもおこなっている。RF 電子銃と加速空洞には高周波のピックアップが無いため、実際には空洞への入力波に対する安定化制御がおこなわれている。また、パルス幅が非常に短いため、フィードバックはパルス間動作である。このシステムの導入で位相ドリフトの変動が大きく抑えられ、大幅に安定度が改善されていることが示された。さらに、ビームトラッキングコード ASTRA を用い、RF の安定度に対するビームのエミッタンス・電荷量・エネルギー変動やスプレッドなどのシミュレーションも行われた。最終的な性能評価としてビームの安定度を測定した。残念ながら、エージングの都合上加速空洞の運転はなされなかったが、RF 電子銃のみの運転において、LLRF フィードバック制御によりビームのエネルギー安定度が明らかに改善し、電荷量も安定することが示された。Popov 氏が LUCX にデジタル LLRF フィードバックシステムを導入したことにより、LUCX におけるレーザー逆コンプトン散乱 X 線光源の研究開発に大きく貢献することが期待される。

Popov Konstantin 氏は、これまで日本加速器学会でポスター発表と口頭発表を各 1 回行い、国際会議・ワークショップ等で 3 回のポスター発表を行っている。このうち国際会議 1 件分のプロシーディングが発表されている。査読付きの論文については、Physical Review Accelerators and Beams (PRAB)に 1 件投稿中である。英語力とプレゼンテーション能力にも問題が無く、審査員全員一致で合格とした。