深圳综合粒子设施研究院
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# An Intra-pulse feedforward algorithm for improving pulsed microwave stability

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# Contents

# 1 Motivation



- In the pulse operation process of the Dalian Coherent Light Source (DCLS) linear accelerator, the klystron plays an important role in the microwave system.
- During operation in DCLS, we found that there is obvious jitter between adjacent microwaves output by klystron.


Figure1 DCLS

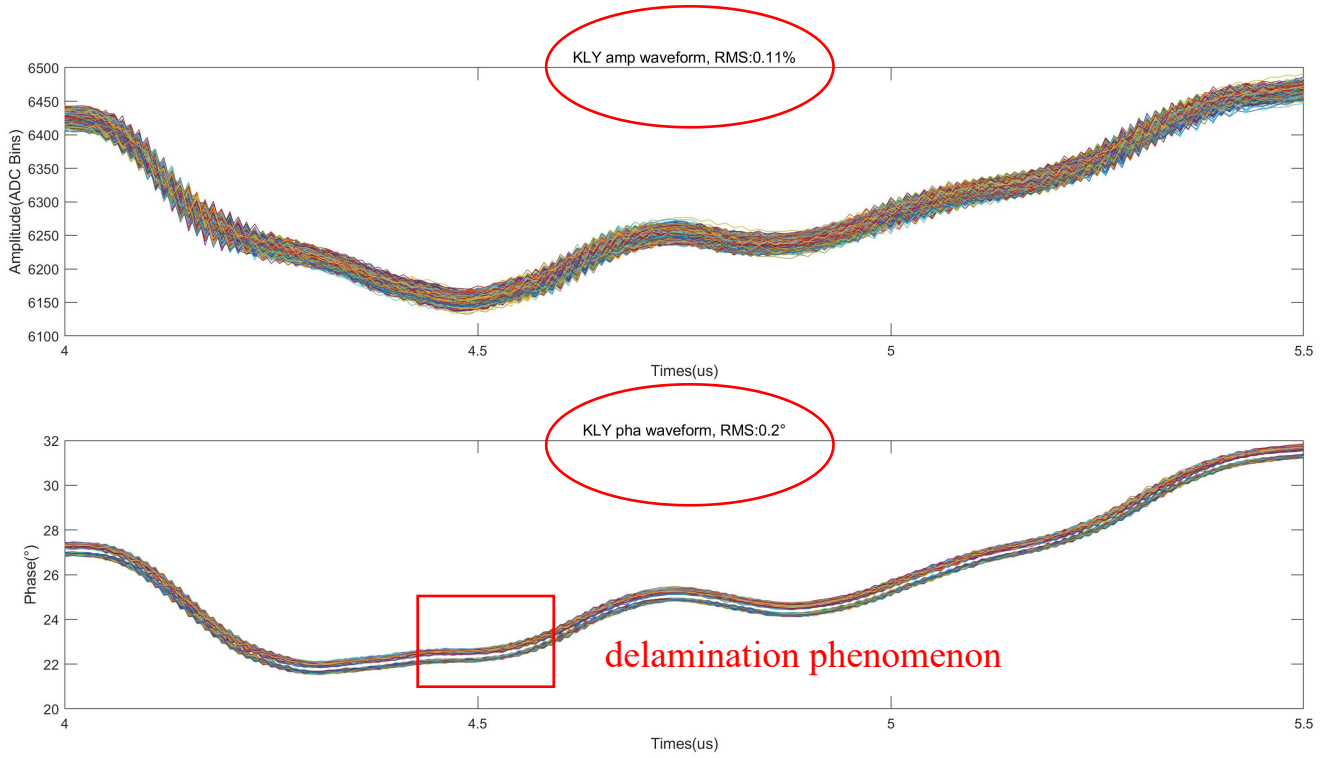


Figure2 Jitter between adjacent microwaves

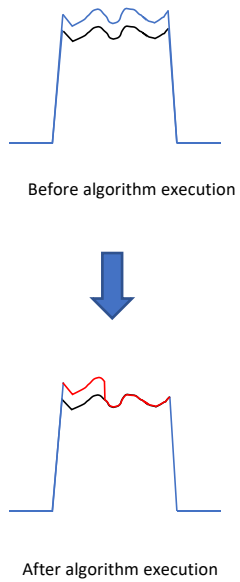


Figure3 Purpose

# 2.1 Model expression of the problem



- **Klystron small-scale linear and amplitude phase jump model:** Physical process → Abstract model → mathematical expression.

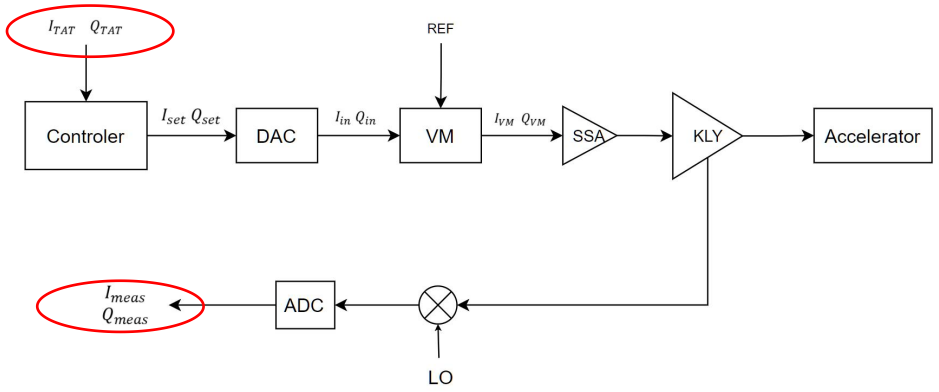


Figure1 The physical process from LLRF excitation to measurement

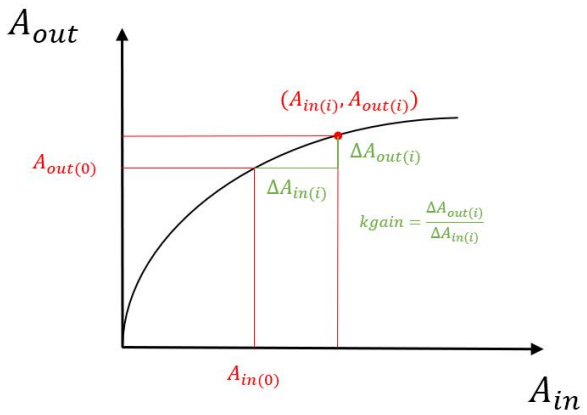


Figure2 The klystron input-output curve

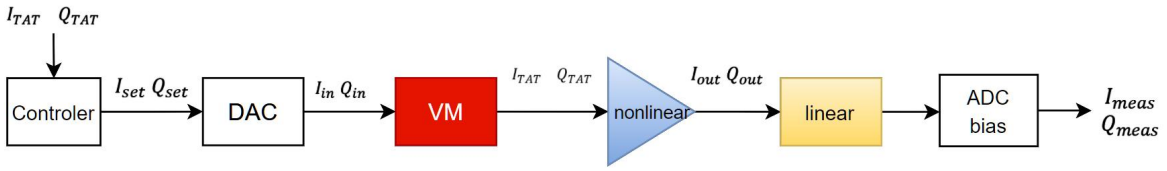


Figure3 The abstract model of the entire loop physical process

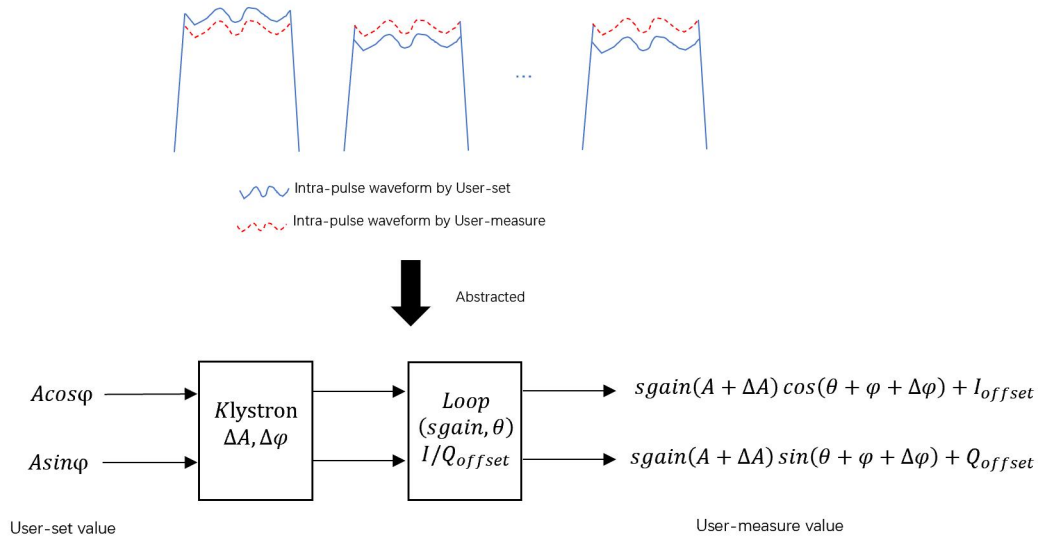


Figure4 The mathematical expression of abstract models

# 2.2 Intra-pulse feedforward algorithm

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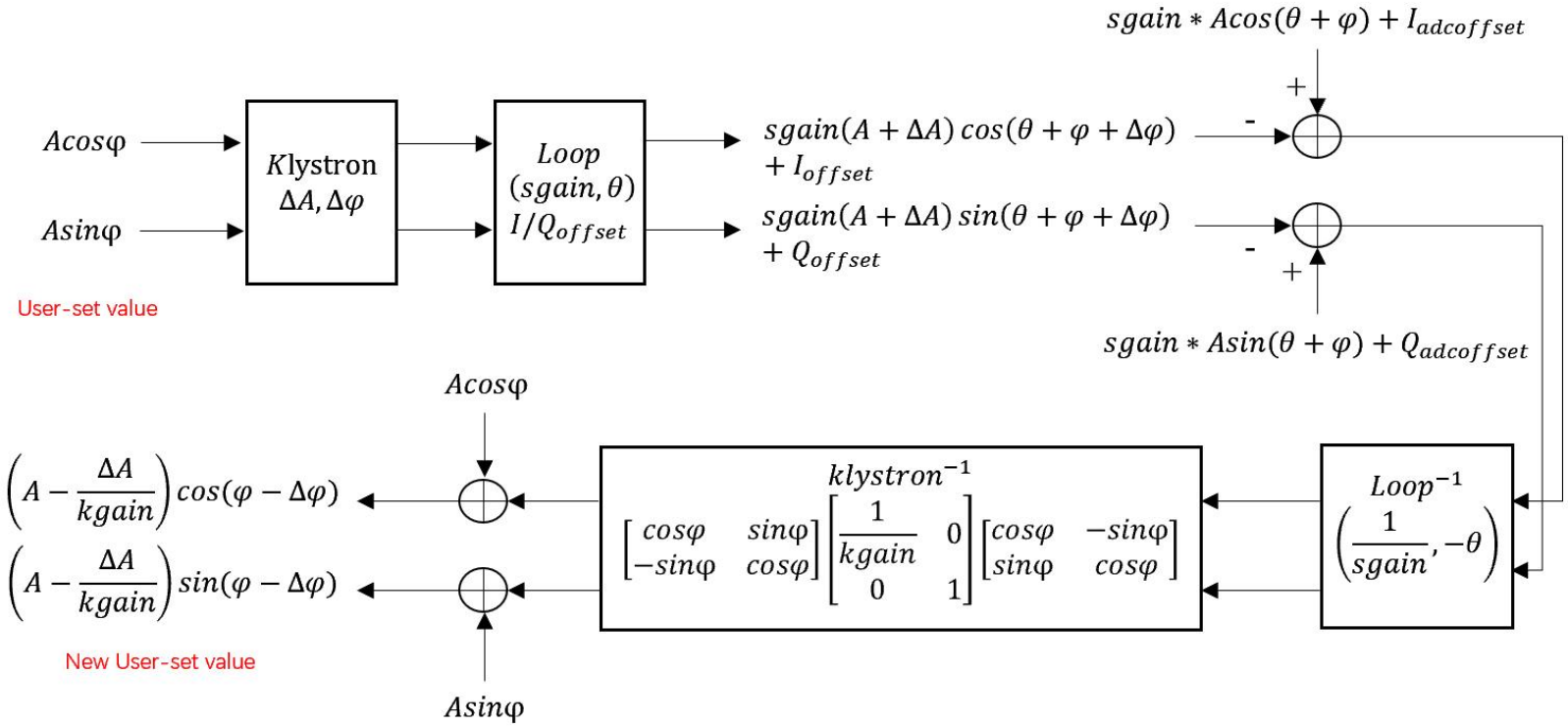
- To solve the problem of klystron amplitude and phase jump in a small-scale linear amplitude and phase jump model, we designed an **intra pulse feedforward algorithm.**

1. Get **the difference** between the measured value and the expected value.
2. **Inverse transformation** of klystron small-scale linear and amplitude phase jump model.
3. **Compensate** for user input values.




Mathematical derivation of intra pulse feedforward algorithm

# 2.3 Key parameter of our algorithm



- According to our model and algorithm, to suppress amplitude and phase jump, it is necessary to measure the loop phase shift($\theta$), loop gain($sgain$) and $kgain$ parameters.

$$\begin{bmatrix} I_{meas} - I_{adcoffset} \\ Q_{meas} - Q_{adcoffset} \end{bmatrix} = \begin{bmatrix} sgain * cos\theta & -sgain * sin\theta \\ sgain * sin\theta' & sgain * cos\theta \end{bmatrix} \begin{bmatrix} Acos\varphi \\ Asin\varphi \end{bmatrix}$$

$$\begin{bmatrix} Acos\varphi \\ Asin\varphi \end{bmatrix} = \begin{bmatrix} X & cos\theta/sgain & sin\theta/sgain \\ Y & -sin\theta/sgain & cos\theta'/sgain \end{bmatrix} \begin{bmatrix} 1 \\ I_{meas} \\ Q_{meas} \end{bmatrix}, \quad \begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} sgain * cos\theta & -sgain * sin\theta \\ sgain * sin\theta & sgain * cos\theta \end{bmatrix}^{-1} \begin{bmatrix} -I_{adcoffset} \\ -Q_{adcoffset} \end{bmatrix}$$

$$[A_1 \quad A_2 \ldots A_n] = [Sgain \quad Sgain * kgain] \begin{bmatrix} A_i & A_i & \cdots & A_i \\ A_1 - A_i & A_2 - A_i & \cdots & A_n - A_i \end{bmatrix}$$

- By fitting multiple sets of measured values and solving those matrix, the loop phase shift($\theta$) loop gain($sgain$) and $kgain$ parameters can be obtained.

# 3.1 Automation application software

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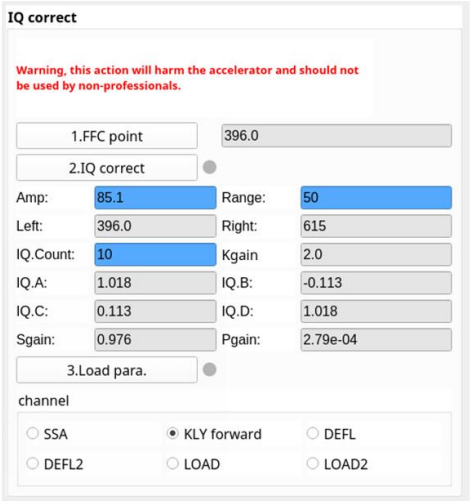
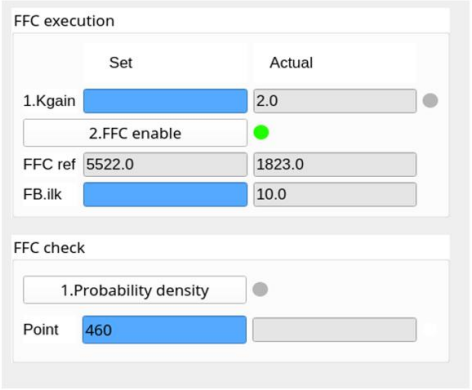
- We created a user GUI application based on PyQt.
- The main functions of the software include: LLRF excitation of amp/pha, calculation of key parameters, intra-pulse feedforward switch, etc.

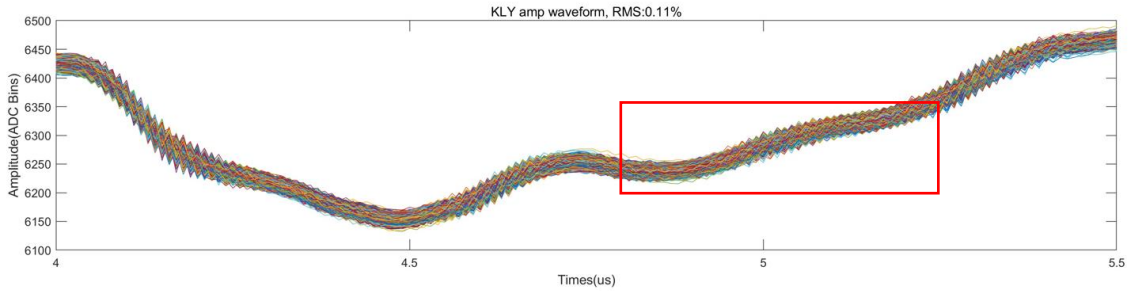



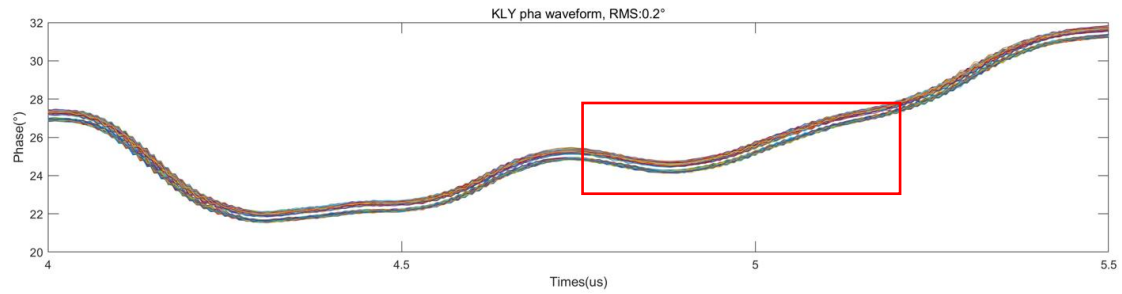



# 3.2 Experimental verification

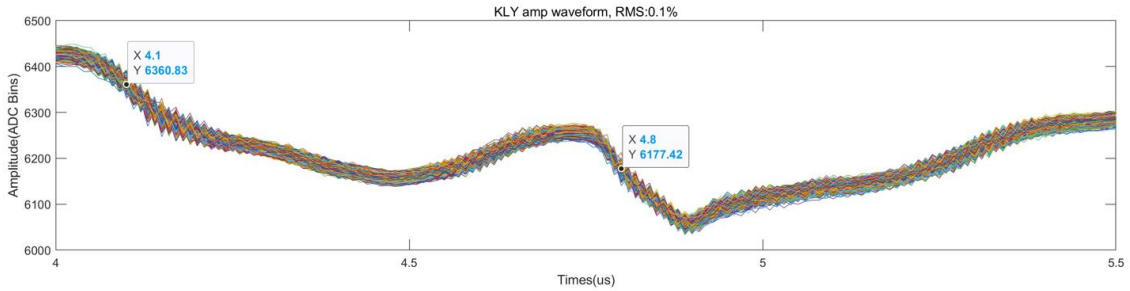


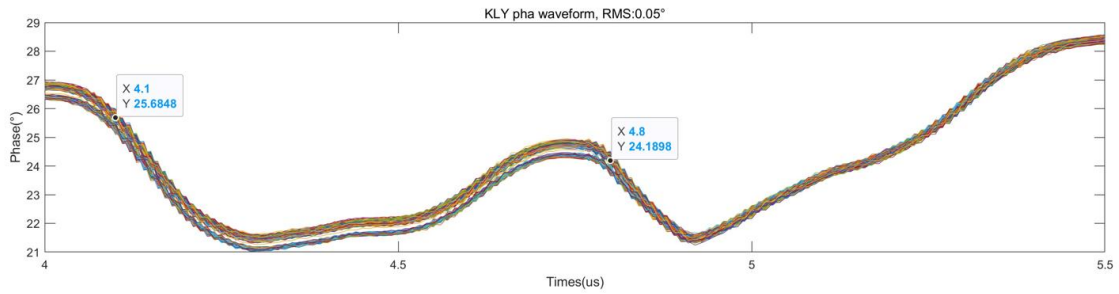
- This algorithm can effectively suppress the jitter between adjacent microwaves and improve the amplitude and phase stability (RMS) **from 0.11%/0.2° to 0.1%/0.05°.**
- It can be seen from the figure that the phase layered jitter phenomenon of microwaves is significantly stronger than the amplitude layered jitter. Therefore, the improvement of microwave phase stability by the algorithm is far better than the improvement of microwave amplitude stability.




Original waveform




Feed-forward waveform

# 4 Conclusion and future work



1. We propose an **intra-pulse feedforward algorithm** based on klystron small-scale linear and amplitude phase jump model.
2. We developed user-level **automation software** that enables our feedforward algorithm.
3. **Verification** was carried out based on DCLS. The results show that our algorithm can effectively suppress the jitter between adjacent microwaves.
4. In the future, we will further accumulate theoretical and practical experience for the Shenzhen medium-energy high repetition rate X-ray free electron laser (S3FEL) device.

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