Pulse-to-Pulse Waveform Analysis for Evaluation of Pulse Compressor System

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Outline

1. Introduction: What is Pulse compressors?
   - Spherical-Cavity type super-compact pulse compressor
   - Development in KEK

2. Analytical method in high-power operation
   - Equivalent Circuit Model
   - Overall Analytical Method

3. Analysis of “abnormal” waveform with large rf reflection (still in progress)
   - Interlock and data-taking system in test-stand
   - “Reconstruction” abnormal waveform

4. Summary and near-term plans

Introduction: What is Pulse Compressors

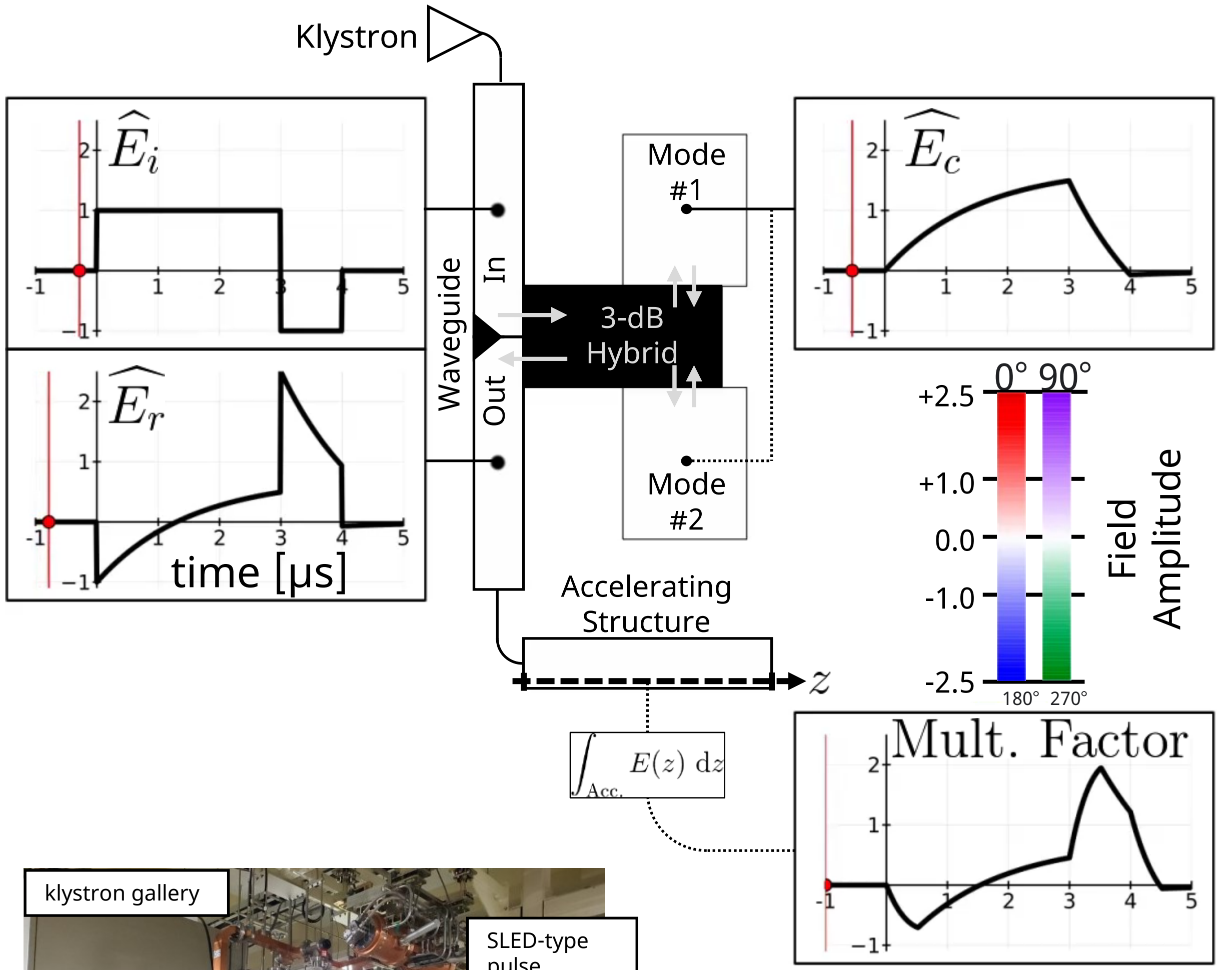
What is Pulse Compressors(PC)?

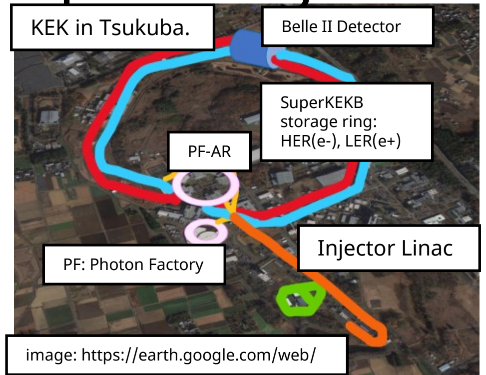
A passive power-amplifier composed of 3-dB hybrid power divider and high-Q rf resonant cavities.

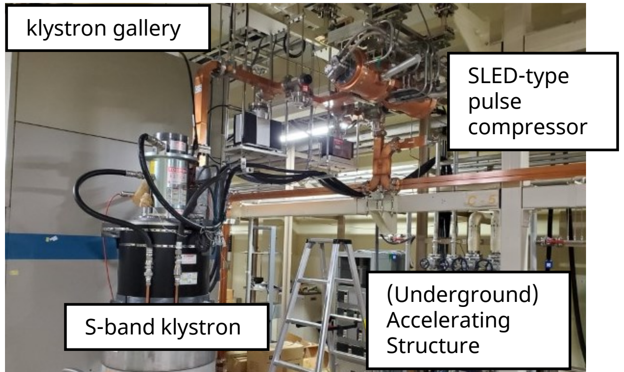
KEK e+/e- injector Linac

provides e+/e- beam to 4 storage lings for SuperKEKB experiment and synchrotron light source.

60 accelerating units are operating from 1990s.



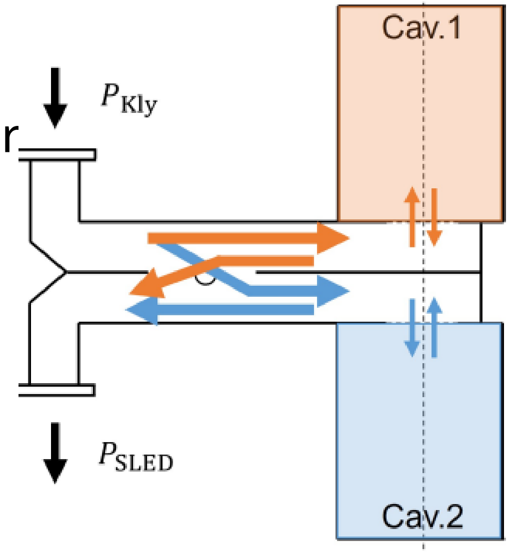




Introduction: SLED vs. SCPC

SLED

SLAC Energy Doubler



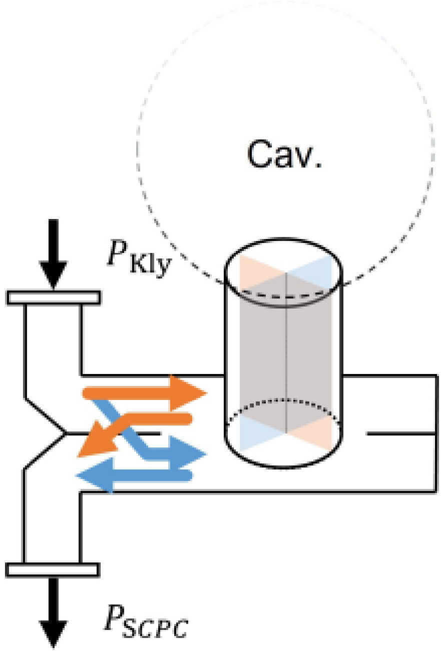
- 3-dB Coupler
- rf cavities x2
  (Cylindrical type)

SLED was developed as the first pulse compressor by SLAC in 1974.

Two rf cavities must be fabricated with high precision.

SCPC

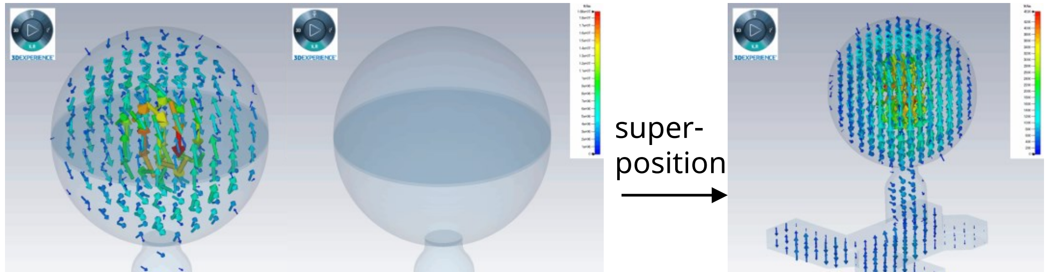
Spherical Cavity type Pulse Compressor



- Mode polarizer
- Axisymmetric rf cavity x1
  (Spherical type)

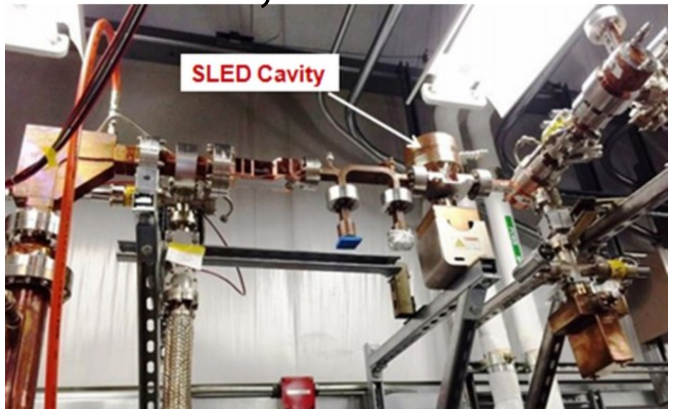
A pulse compressor with only one resonant cavity was invented by SLAC in 2016.

Two orthogonal rf $TE_{\{1,1,2\}}$ modes were degenerated in the cavity.



Development of SCPC

X-Band; SLAC-LCLS[1]



S-Band; Tsinghua Univ.[2]

Jointly with Tsinghua University group, we chose and developed SCPC type in the viewpoints of

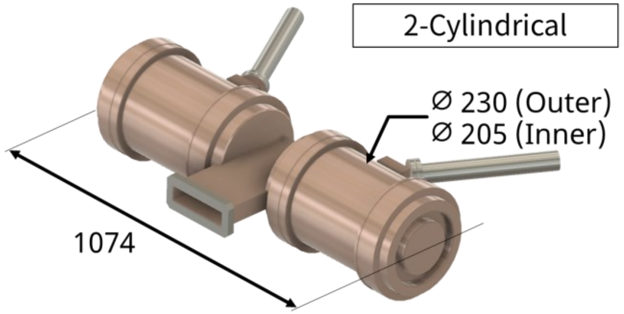
- stability in high-power operation: improved in water cooling performance
- cost-efficiency and suitable for mass production: compactness, fewer parts and brazing process.

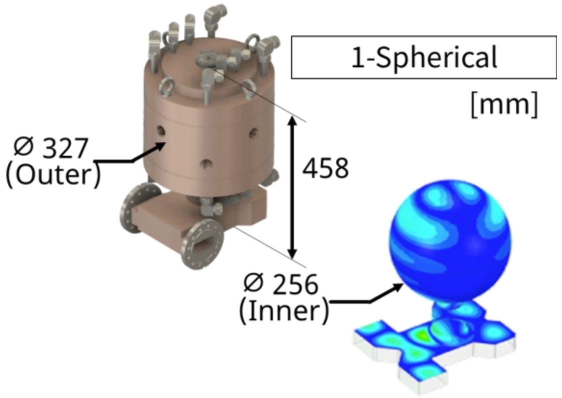
as a substitutive machine：

→ same rf parameters

→ same waveforms

(amplification, decay time, … etc)

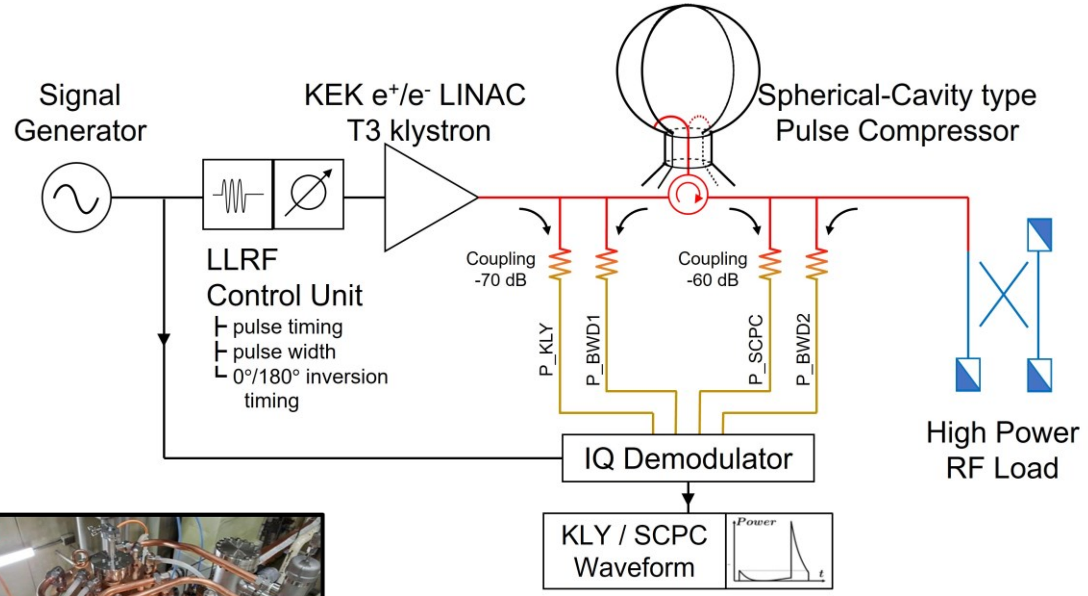




specifications are from [3]

[1] J. W. Wang, *et al.* PRAB **20**, 110401, 2017.
[2] P. Wang, *et al.* IPAC2018, THPAL153, 2018.
[3 I. Sato, *et al*. ed. KEK-Report 95-18, 1996.

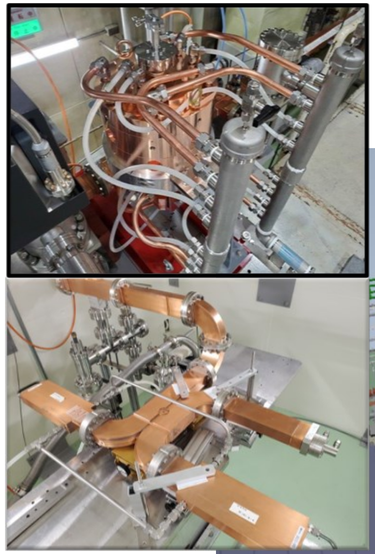
High-Power Operation: Schematic view of test stand

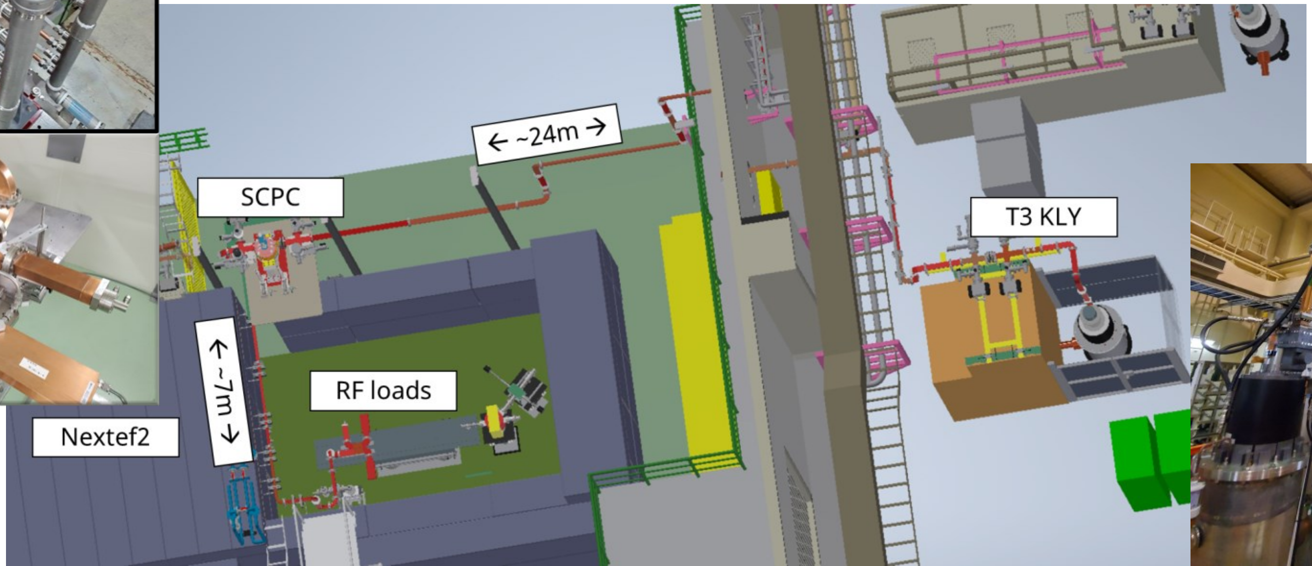


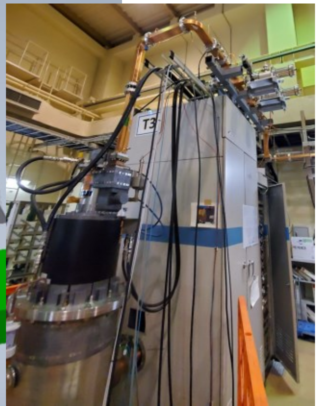
One *prototype* was fabricated in March 2021, and one *production equipment* in March 2022.

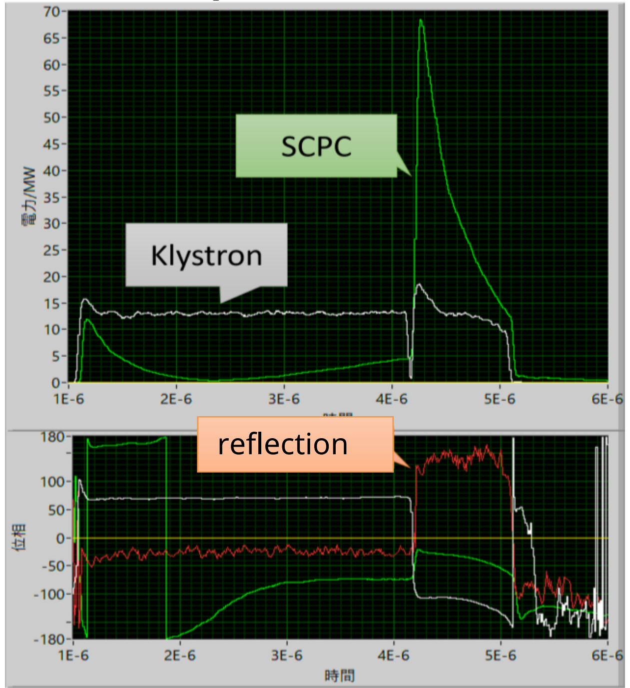
1 klystron and 1 SCPC, the output was directly connected to the rf dummy-loads.

RF power is monitored before/after SCPC for each direction.









Motivation for pulse-to-pulse analysis

In the high-power test, we get waveform data, quite different from frequency domain measurement (such as VNAs).

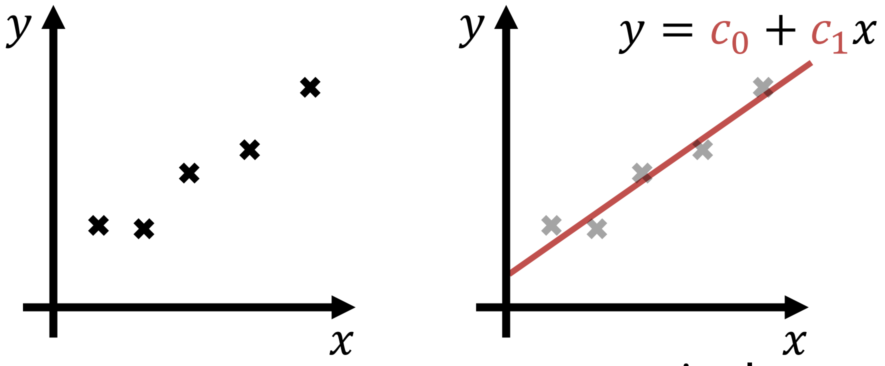
The performance of an rf device is usually evaluated in rf parameters (such as $f_c, Q_0, Q_L, \beta, \ldots$), some of which cannot directly derived from time-domain measurement.

Real-time analysis in high-power operation is needed …

1. to ensure the device-under-test works as expected
2. to protect the device in the measurement system
3. to provide a policy for analysis of abnomal pulse.

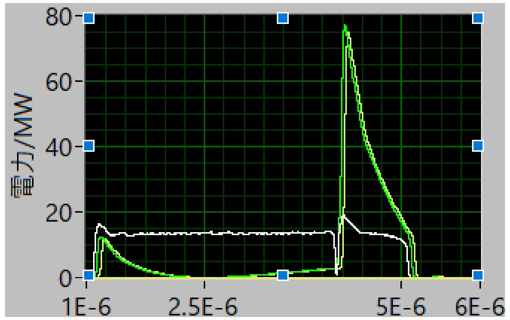
search for the set of parameters which satisfies input-output relationship in equivalent circuit model

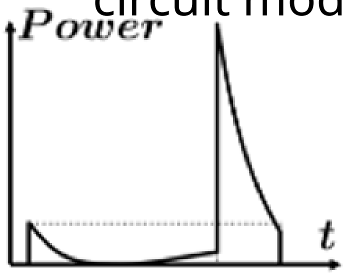
Curve fitting



equivalent circuit model

Pulse compressor system





Equivalent circuit model

The behavior of pulse compressor can be written as[4]:

$$T_c \cdot \frac{\mathrm{d}V_c}{\mathrm{d}t} + V_c = \alpha V_i$$

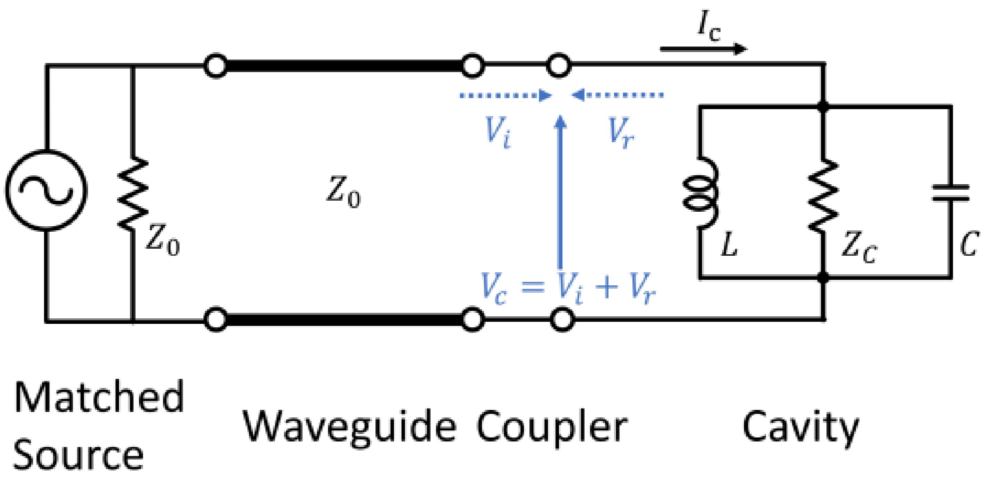
but this equation is not sufficient in the situation where frequency of input (f) and resonant frequency of rf modes in the cavity (f_c) are different.

E-field amplitude in the cavity

$$\left(1+\frac{\omega_c^2}{\omega^2}\right)\frac{\mathrm{d}V_c}{\mathrm{d}t} + \left\{\frac{\omega_c}{Q_\mathrm{L}} + j\omega\left(1-\frac{\omega_c^2}{\omega^2}\right)\right\}V_c = \frac{2\omega_c\beta}{Q_0}V_i$$

rf parameters which represents cavity characteristics

- $\omega_c = 2\pi f_c$: resonance frequency
- Q_0 : Unloaded Q
- Q_L : Loaded Q
- $\beta = \frac{Q_0}{Q_{ext}} = \frac{Q_0}{Q_L} - 1$: Coupling coefficient

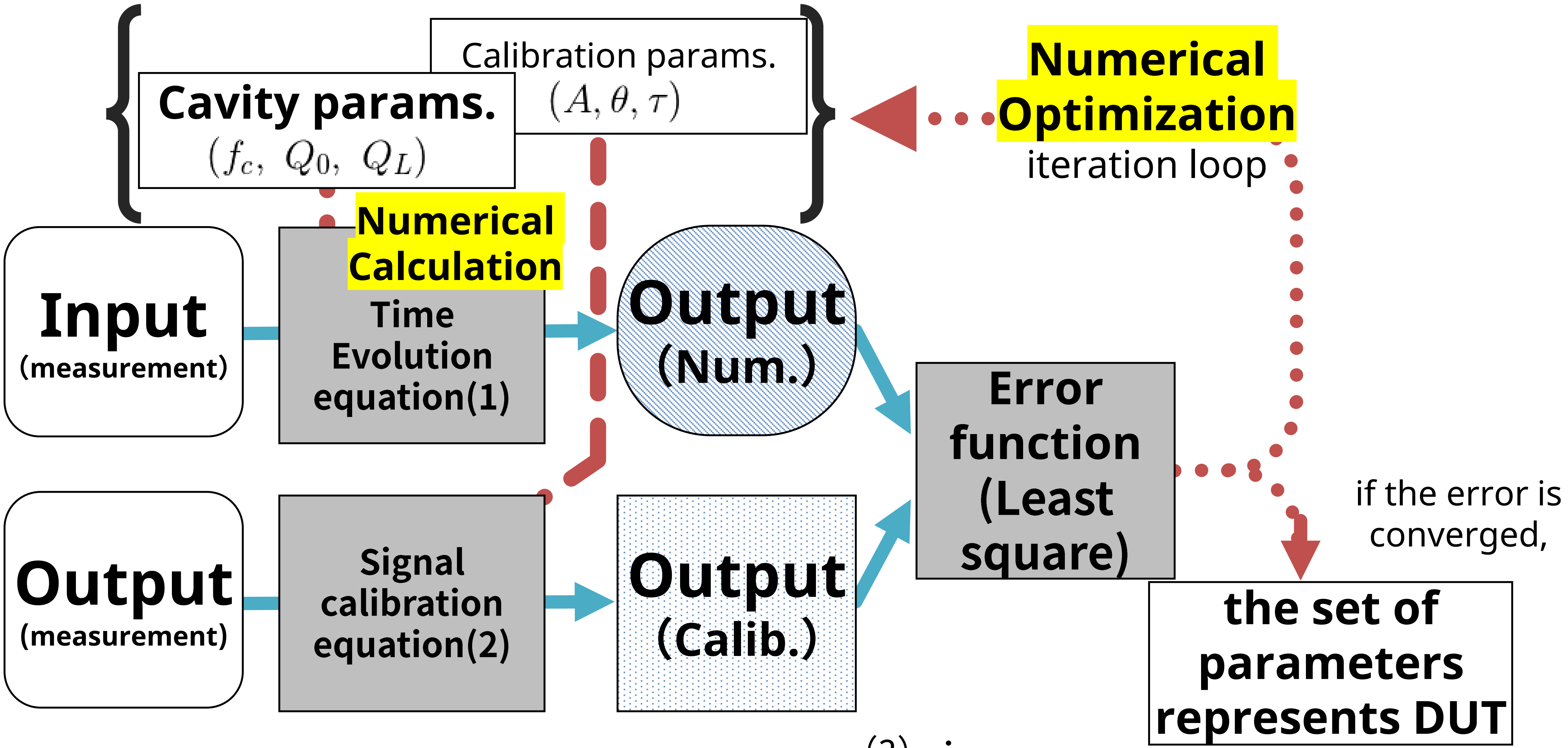


[assumption]:

- two modes(/cavities) have the same rf parameters,
- ideal 3-dB hybrid.

[4] Z. D. Farkas, et al, in *Proceedings of 9th International Conference on High Energy Accelerators*, p.576, 1974.

Analytical Method



(1) :

$$\left(1+\frac{\omega_c^2}{\omega^2}\right)\frac{\mathrm{d}V_c}{\mathrm{d}t}+\left\{\frac{\omega_c}{Q_\mathrm{L}}+j\omega\left(1-\frac{\omega_c^2}{\omega^2}\right)\right\}V_c=\frac{2\omega_c\beta}{Q_0}V_i$$

(2) :

$$\begin{cases} P_{\mathrm{o,meas}}^{(\mathrm{calib.})}(t) = A^2 e^{j2\theta} P_{\mathrm{o,meas}}(t-\tau) \\ V_{\mathrm{o,meas}}^{(\mathrm{calib.})}(t) = A e^{j\theta} V_{\mathrm{o,meas}}(t-\tau) \end{cases}$$

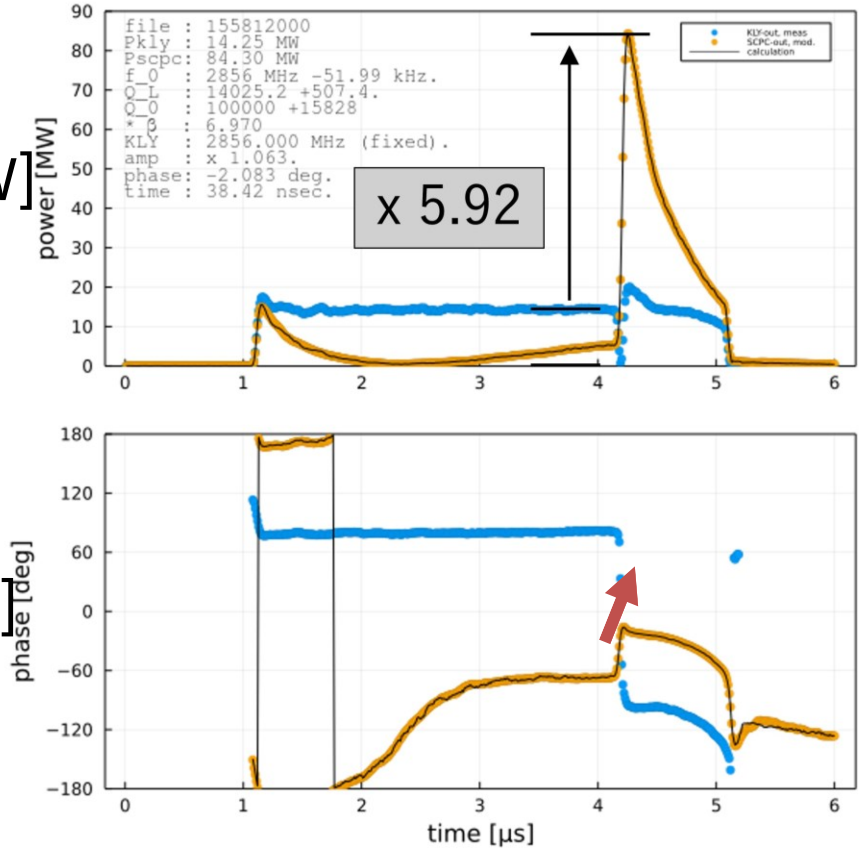
Comparison between measured data and calculation

Blue: Input (measured) | Orange: Output (calib.) | Black: Output (num. calc.)

input: 2. 856 000 GHz

Power [MW]

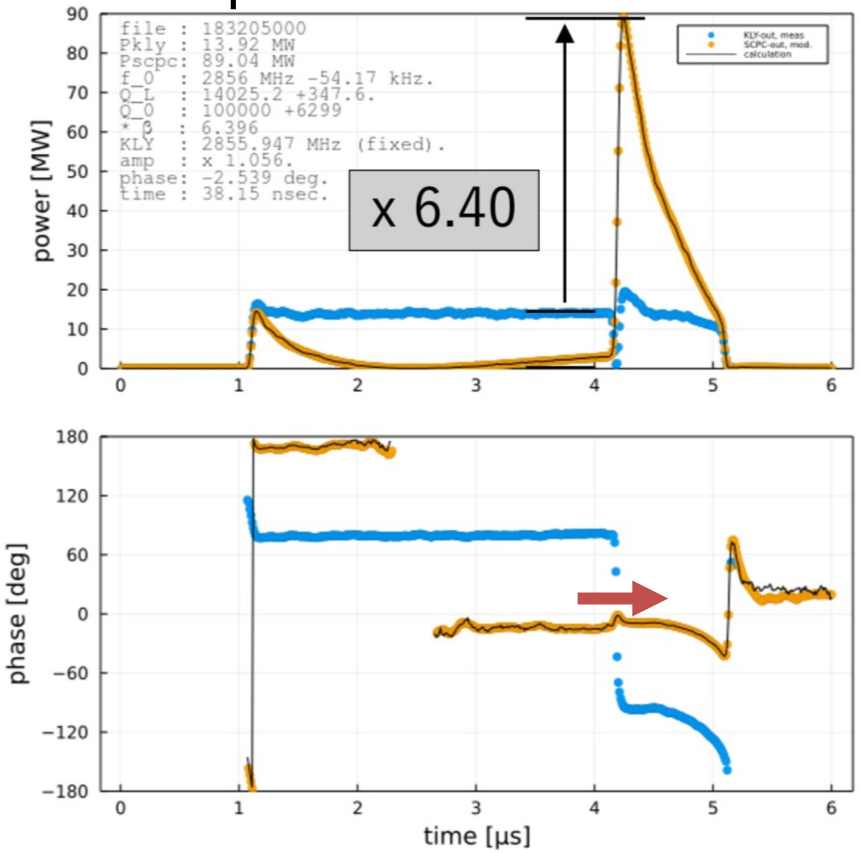
Angle [deg]



Modulated input wave frequency by -53 kHz

SCPC tuning test was yet to be done at this test.

input: 2. 855 947 GHz



The phase shift comes from frequency mismatch.

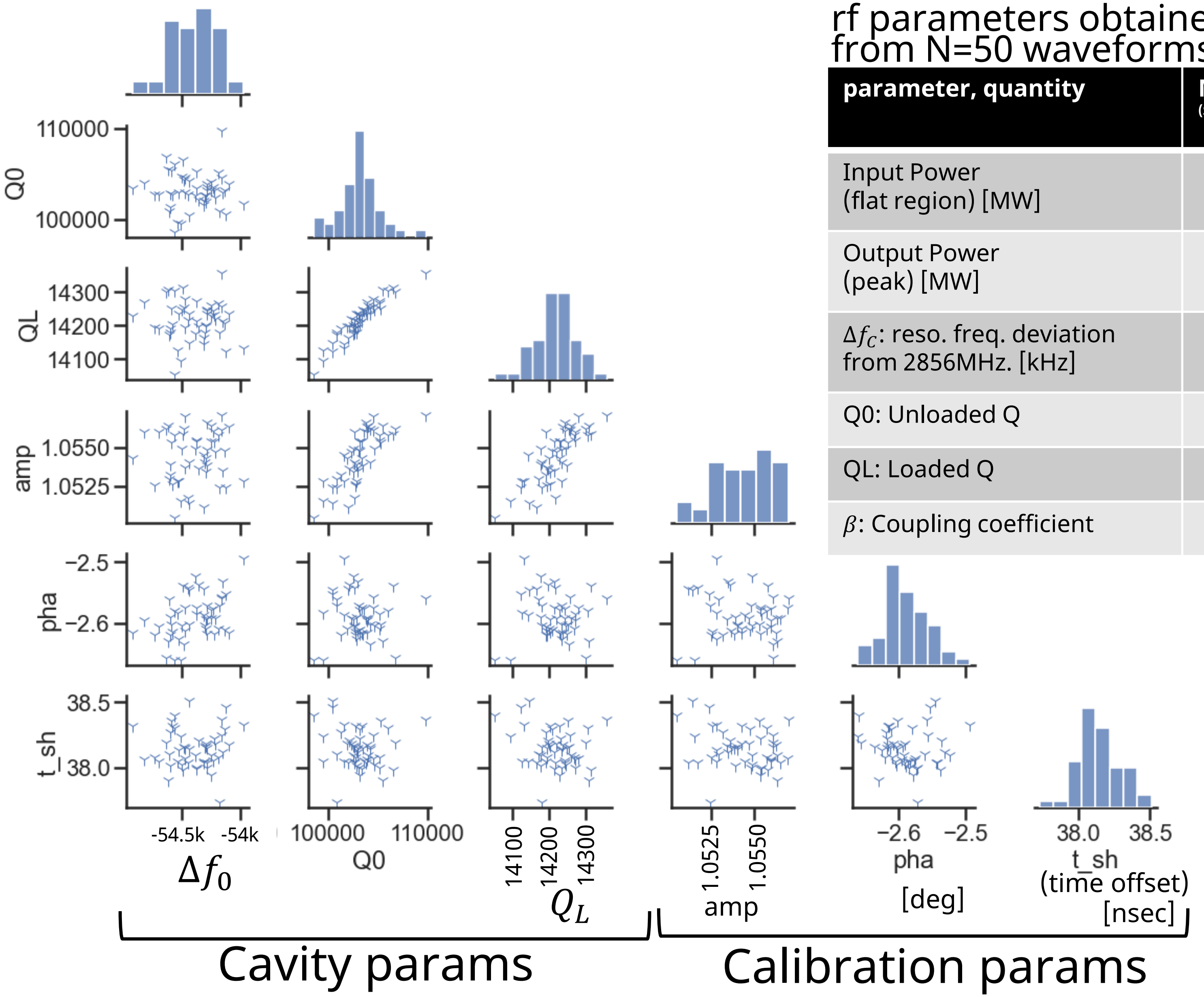
Optimized parameters seem to be reasonable compared with the VNA measurement.

Fitting parameters distributions after optimization

Histogram and correlation plot for 6 fitting parameters (50 pulse data).

There are some difficulties relating to solving an inverse problem.

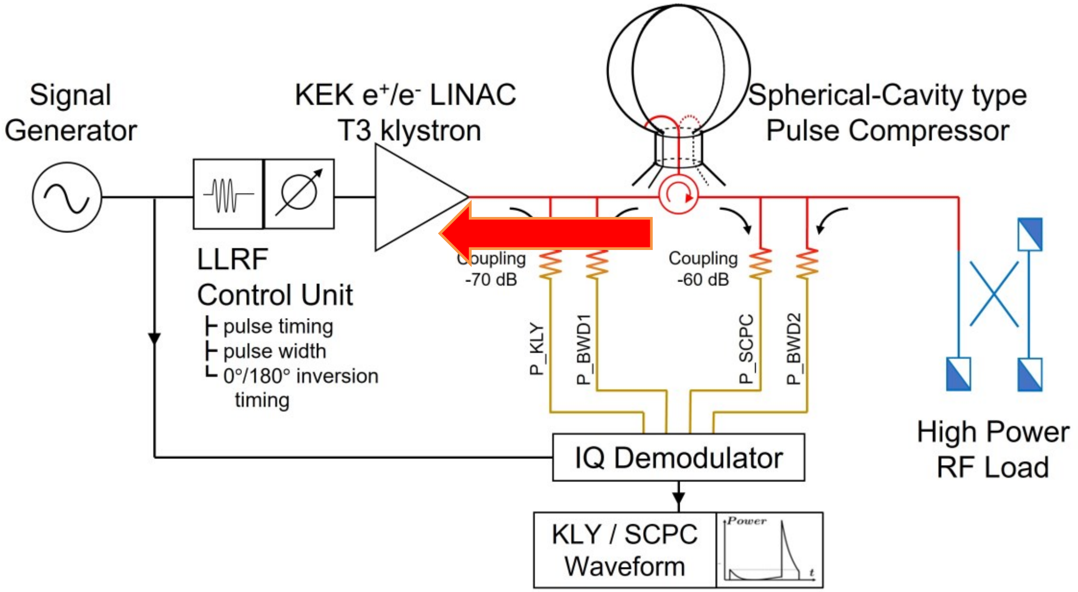
For now, I took many (~100) pulse data in the short time and analyze them in this analytical method.

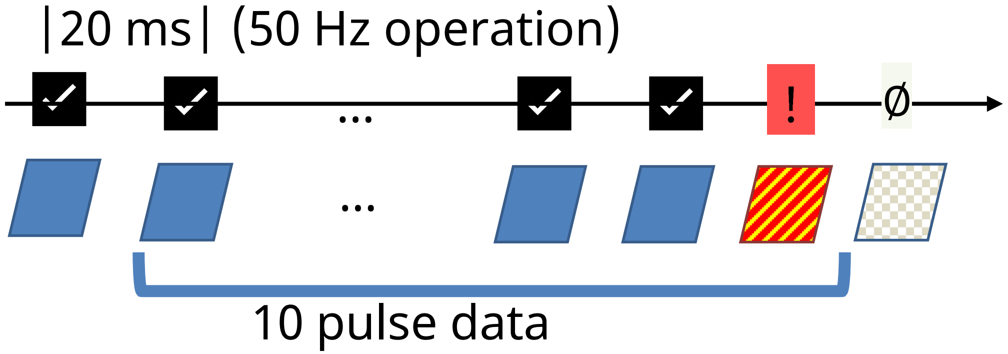


rf parameters obtained from N=50 waveforms

parameter, quantity	Mean Value (StDev in parentheses)
Input Power (flat region) [MW]	13.68(.7)
Output Power (peak) [MW]	87.6(.4)
Δf_C: reso. freq. deviation from 2856MHz. [kHz]	-54.4(.2)
Q0: Unloaded Q	103300(1800)
QL: Loaded Q	14220 (50)
β: Coupling coefficient	6.26(.10)

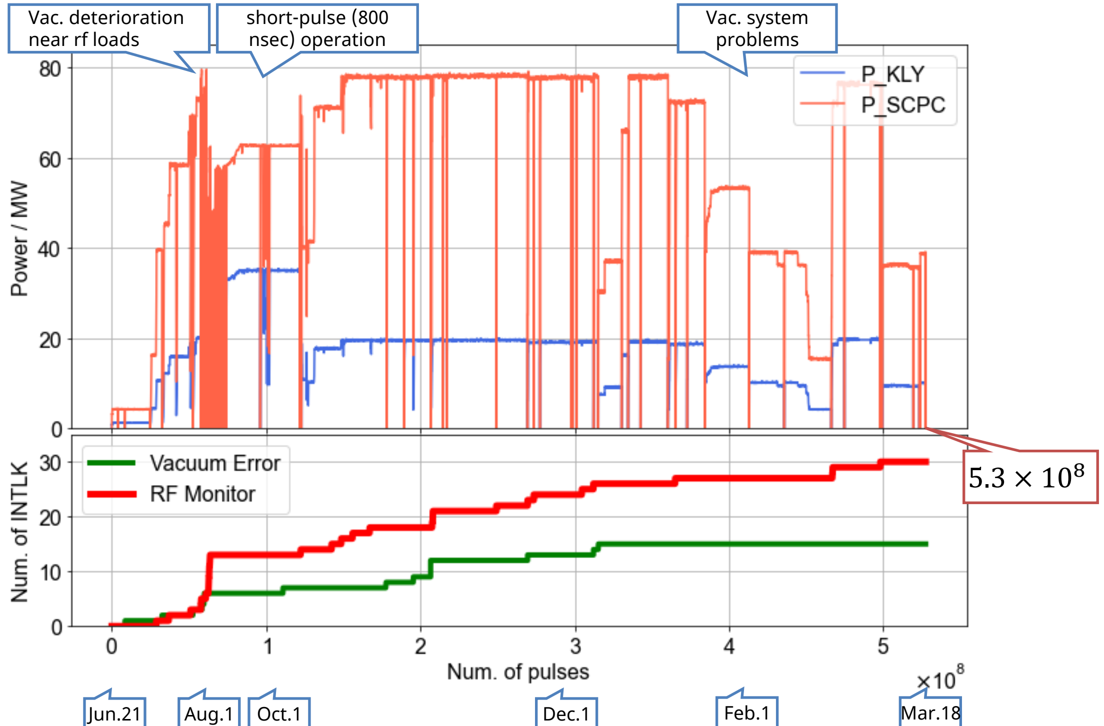
Abnormal pulse analysis: Interlock & data acquisition system.





There are RF Monitors connected to the interlock systems which alerts when it detects high-power rf ($\gtrsim$ 1 MW) propagating backward to the klystron.

When the INTLK system alerted, the abnormal pulse data and previous 10 pulse data are saved as external files.

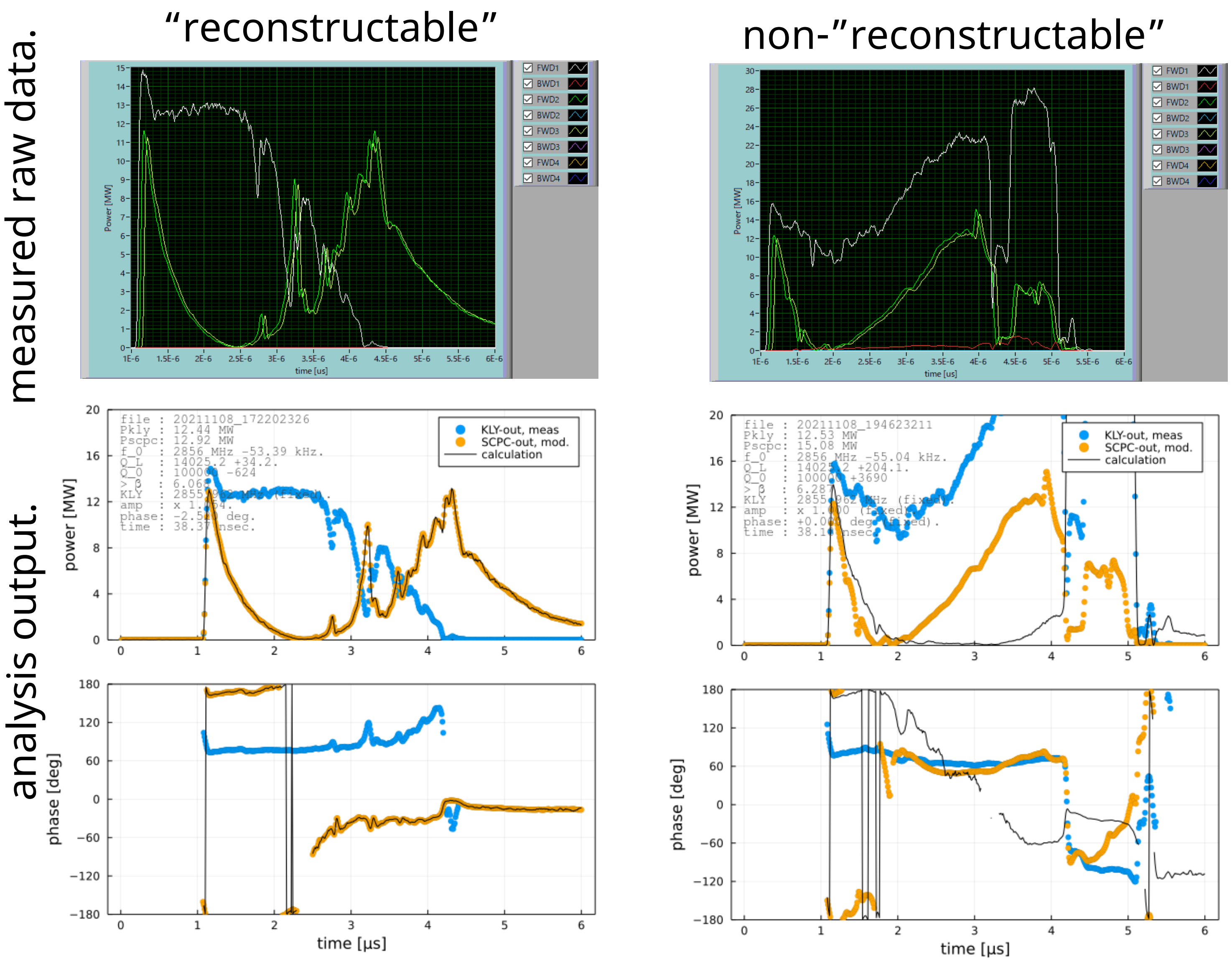


Reconstruction (output waveform from input) of abnormal waveform

There are some reconstructable abnormal waveforms and not ones.

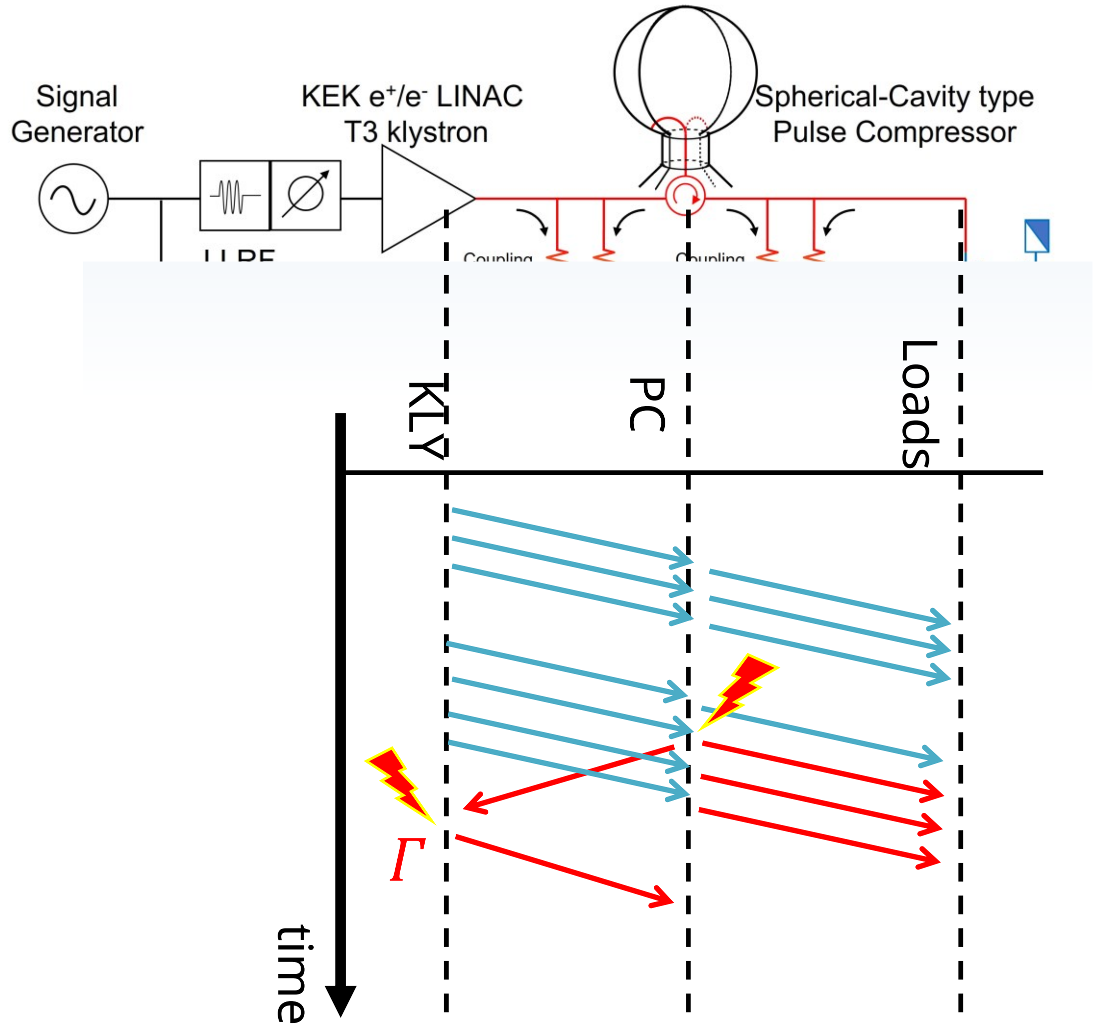
The "reconstructable" one assumed to be directly caused by a failure of the klystron, pulse compressor works correctly.

On the other hands, in the non-"reconstructable" one, the pulse compressor's behavior cannot be represented by the previous circuit model.



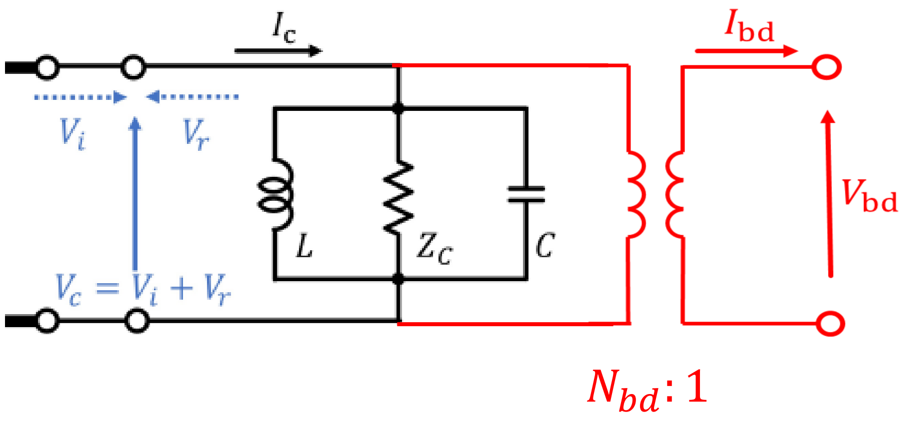
Some policies to tackle non-"reconstructable" waveforms

1) Timeline Analysis



2) upgrading equivalent circuit model

New coupling to the cavity with transformer ratio N_{bd}, which was proposed for the analysis of R_{bd} in accelerator structure [5].



[5] J. Paszkiewicz, PhD thesis, 2020.

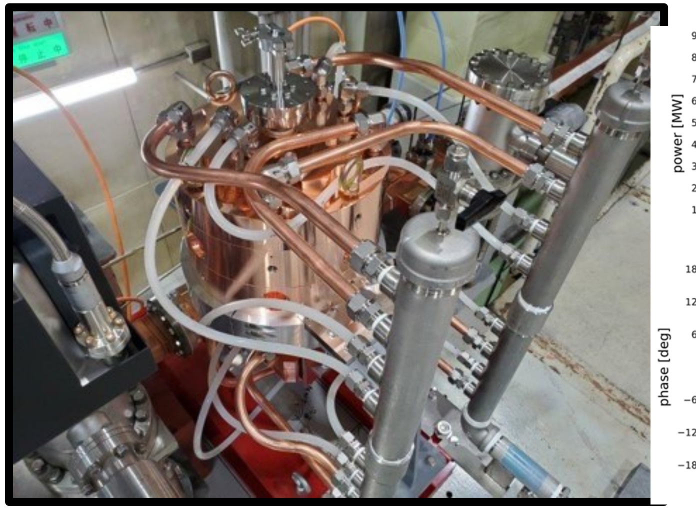
Summary

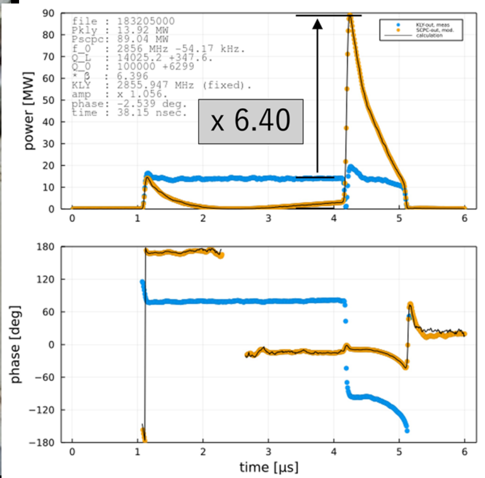
Conclusion:

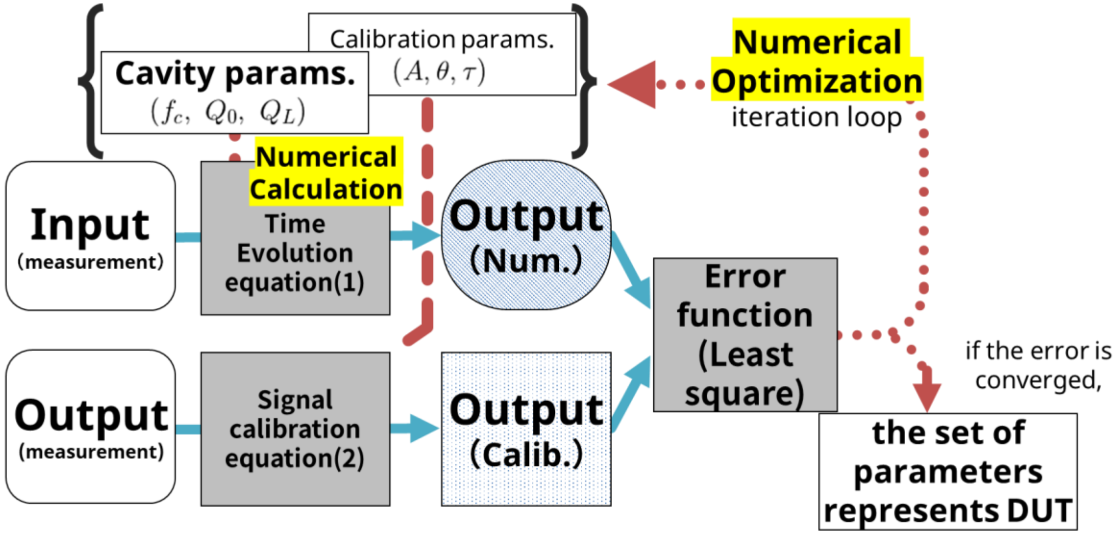
Spherical Cavity type Pulse Compressor (SCPC) is a SLED-type pulse compressor, but it consists of only one spherical cavity, which leads to the **compactness** feature and **cost-efficiency**.

In KEK injector Linac, the prototype was fabricated in May 2021, and one production equipment was in May 2022. High-power operation has begun since June 2021.

Using techniques in Numerical Calculation and Numerical Optimization, I developed an analytical method to acquire rf parameter from the waveform in high-power operation.







$$\left(1+\frac{\omega_c^2}{\omega^2}\right)\frac{\mathrm{d}V_c}{\mathrm{d}t}+\left\{\frac{\omega_c}{Q_\mathrm{L}}+j\omega\left(1-\frac{\omega_c^2}{\omega^2}\right)\right\}V_c=\frac{2\omega_c\beta}{Q_0}V_i$$

Near-time plans:

- Abnormal waveform analysis of non-"reconfigurable" ones
- Establishment of dimple tuning methodology in SCPC
- Real-time pulse-to-pulse analysis
- High-power operation with improvement of RF dummy loads.

Thanks for listening!

References

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2. P. Wang, D.Z. Cao, H.B. Chen, C. Cheng, J. Shi, Z.H. Wang, and H. Zha, High Power Test of the S-Band Spherical Pulse Compressor at Tsinghua University, in *Proc. 9th International Particle Accelerator Conference (IPAC'18),* 2018.
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4. Z. D. Farkas, H. A. Hogg, G. A. Loew, and P. B. Wilson, in *Proc. of 9th International Conference on High Energy Accelerators, (SLAC, 1974)*, p. 576.
5. J. Paszkiewicz, Studies of Breakdown and Pre-Breakdown Phenomena in High Gradient Accelerating Structures. 2020. Oxford U, PhD dissertation. *CERN Document Server*, https://cds.cern.ch/record/2749494