



INSTRUMENTATION
TECHNOLOGIES



LIBERA





Intra-Pulse RF Phase Stabilization in LLRF Systems

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Outline

- Introduction to LLRF systems
- Intra-pulse feedback concept
- Feedback system prototype design, features and laboratory evaluation
- SPARC-Lab testing and results
- Integration into Libera LLRF

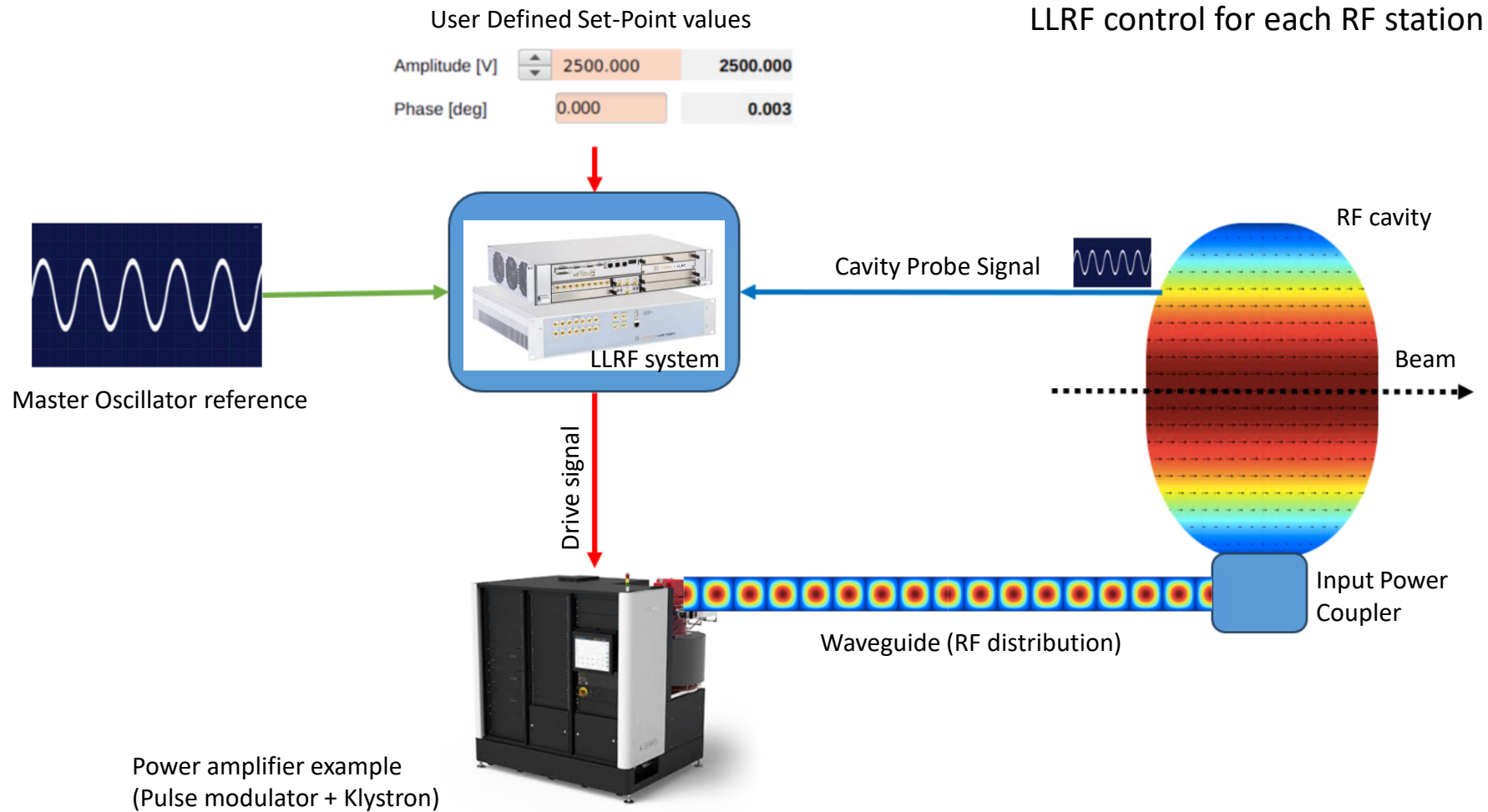


Outline

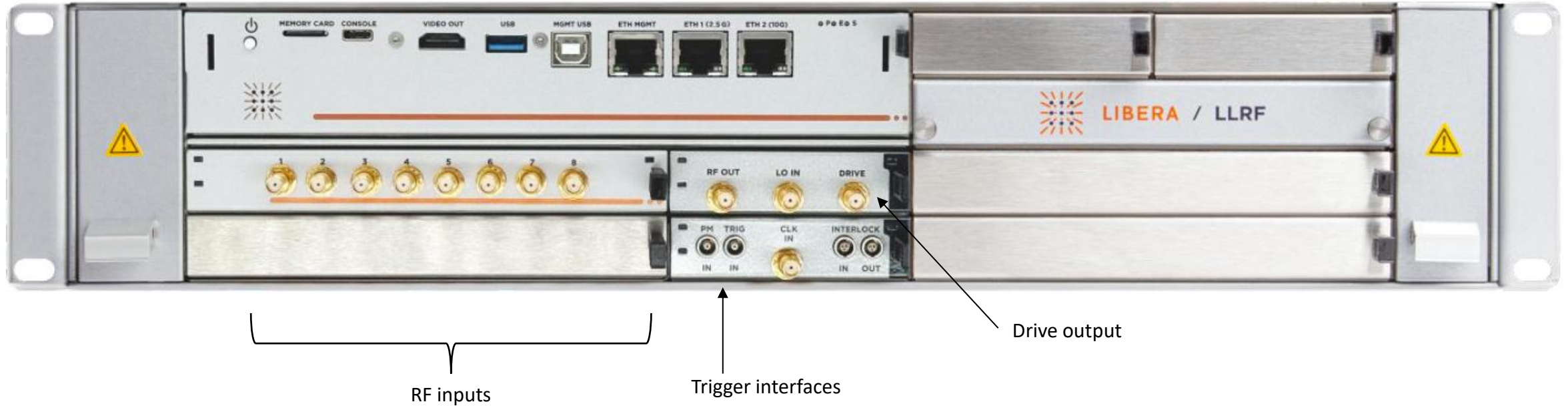
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Digital LLRF brief introduction



Short Libera LLRF introduction



- Digital LLRF platform for pulsed accelerator RF systems
- MTCA-based, 19" 2U modular system
- Scalable RF acquisition: 8 channels per ADC module, up to 250 MS/s per channel
- FPGA-based real-time amplitude and phase processing
- MO-synchronous timing with external trigger inputs
- Amplitude/phase feedback and feed-forward, with integrated RF diagnostics

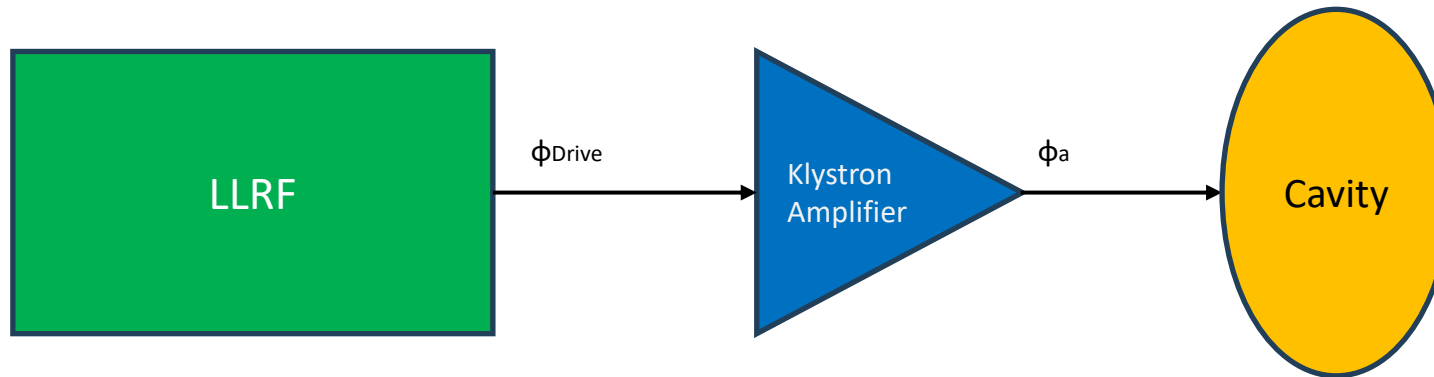
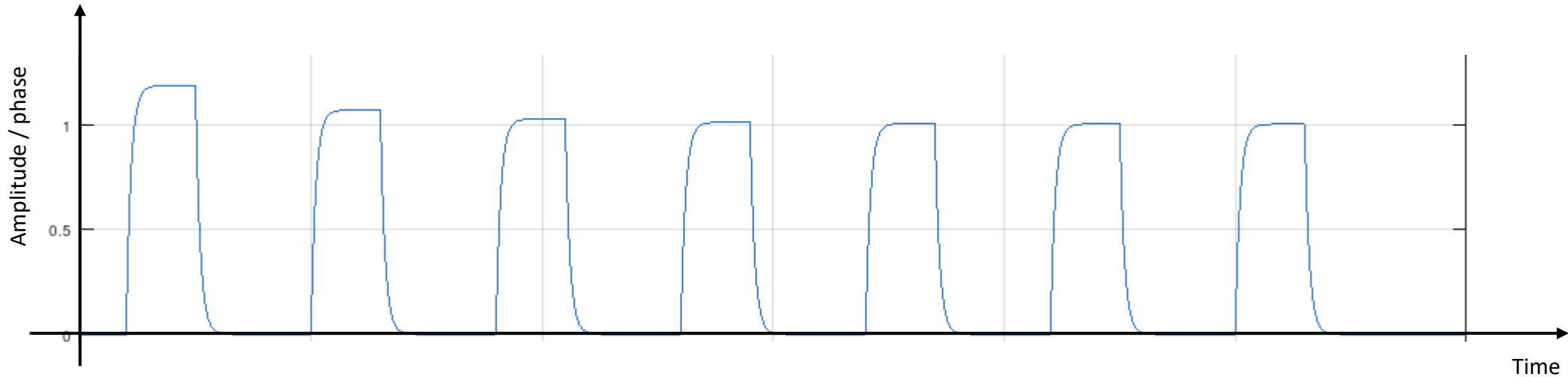
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- **Intra-pulse feedback concept**
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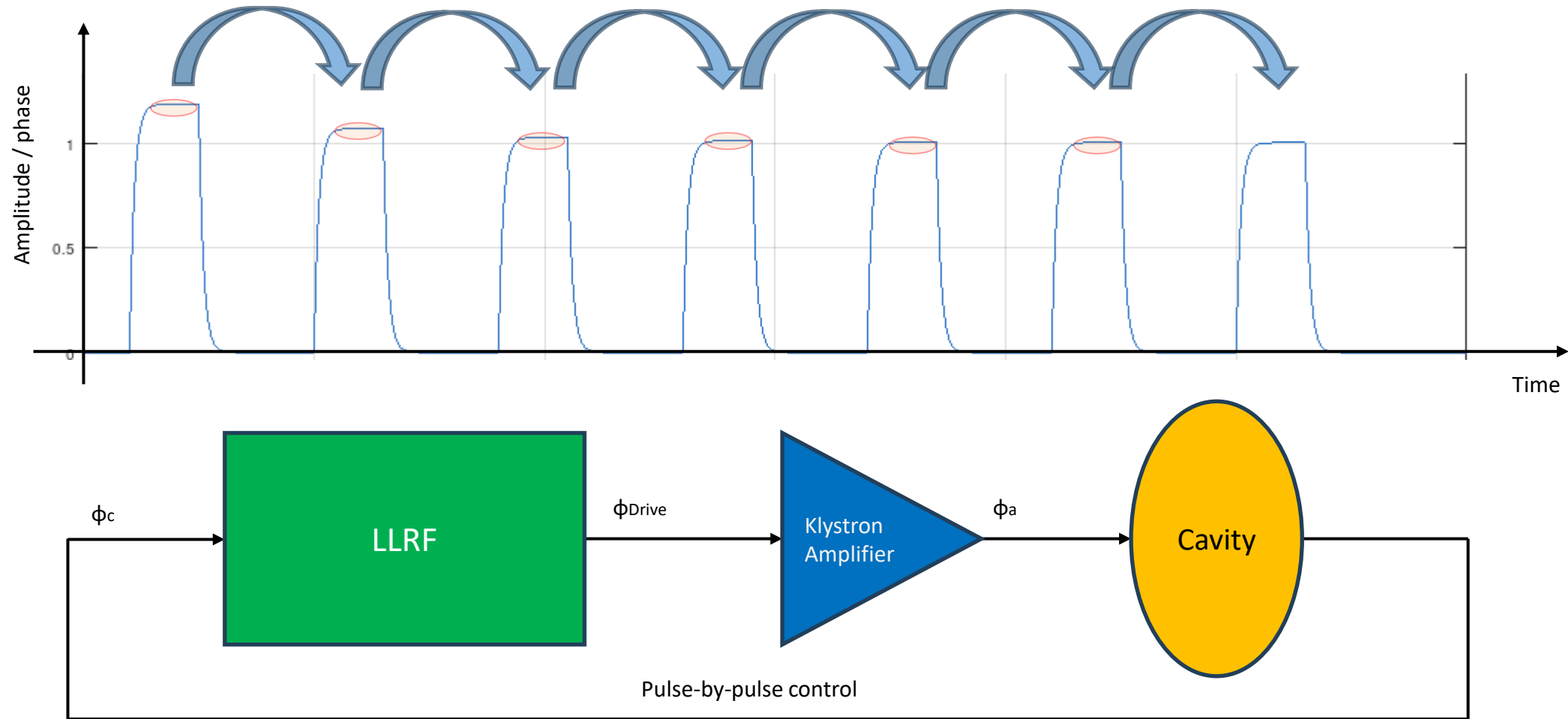
Introduction to short pulse LLRF Systems

Short-pulse electron LINACs, typically operating with RF pulses below 10 μs .



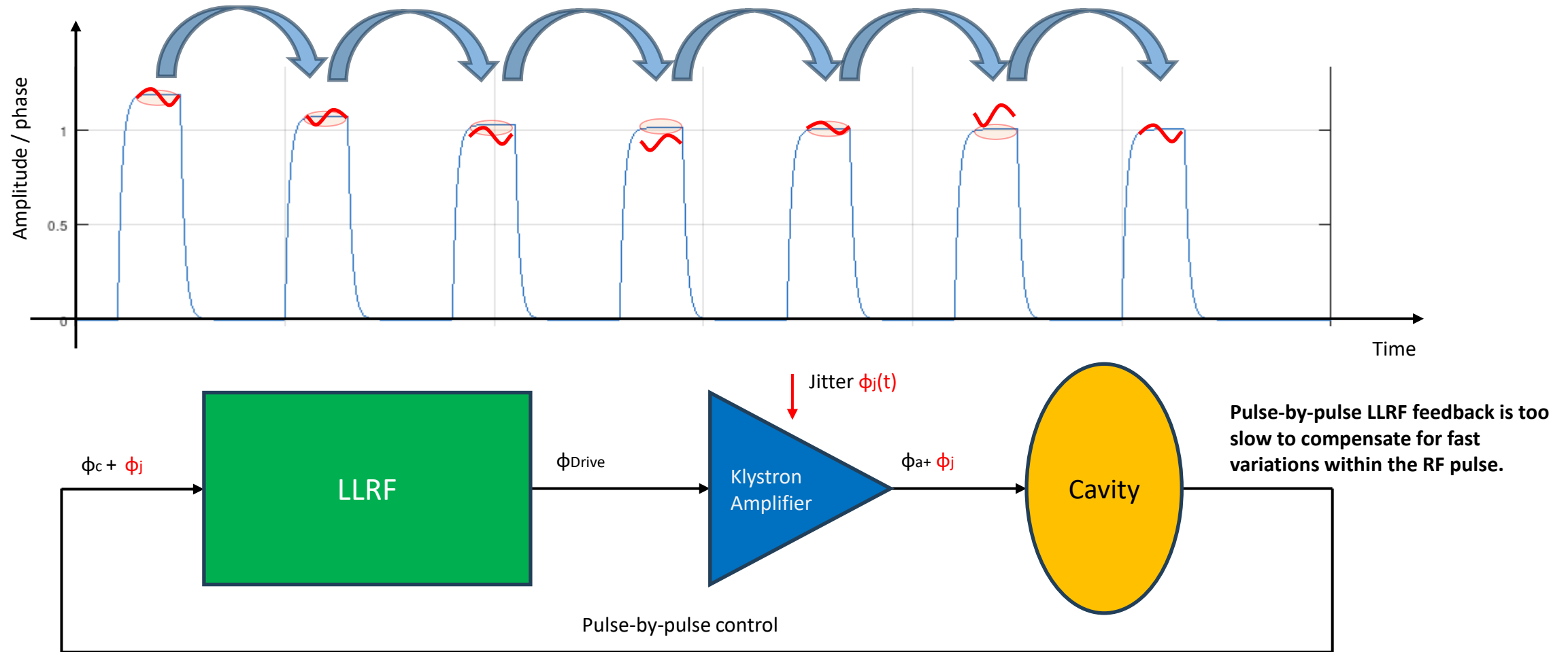
Introduction to short pulse LLRF Systems

Short-pulse electron LINACs, typically operating with RF pulses below 10 μs , generally adopt **pulse-by-pulse LLRF control**.

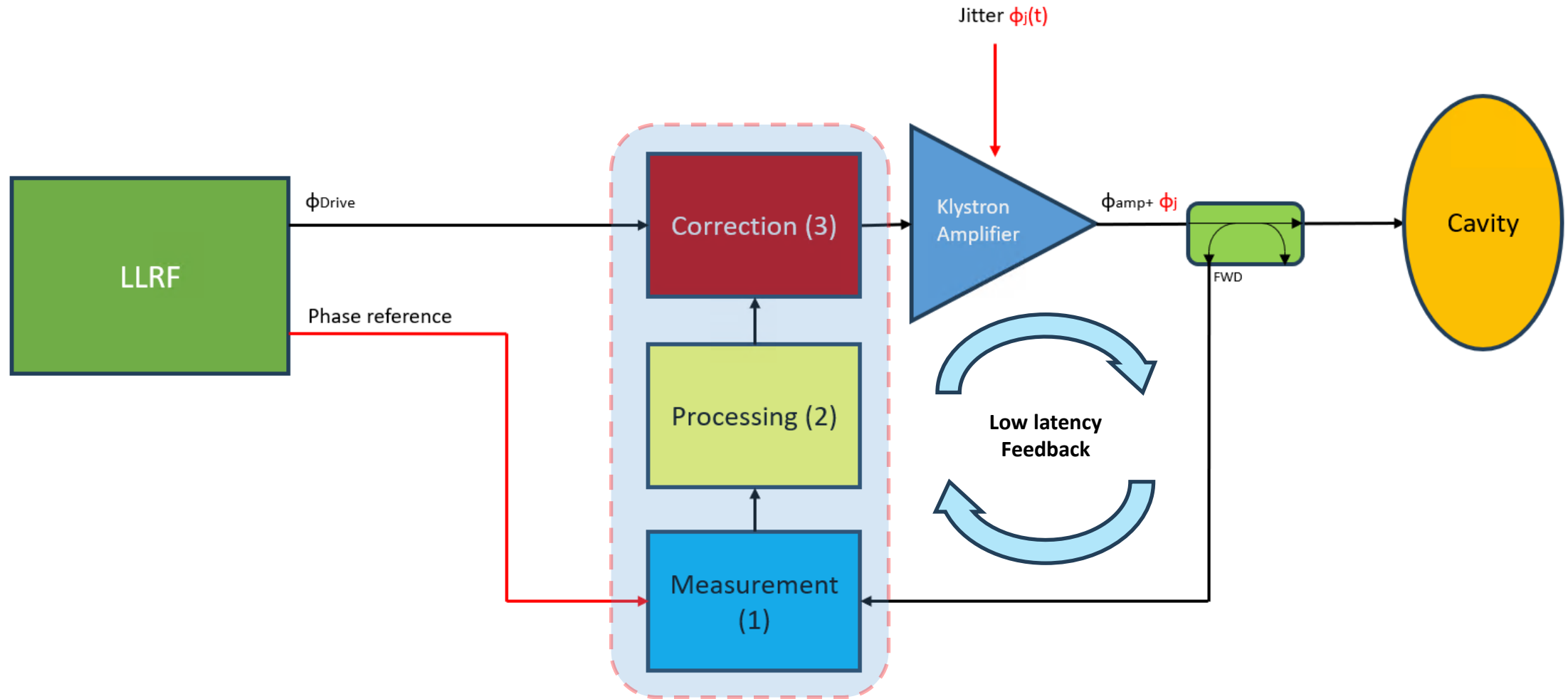


Introduction to short pulse LLRF Systems

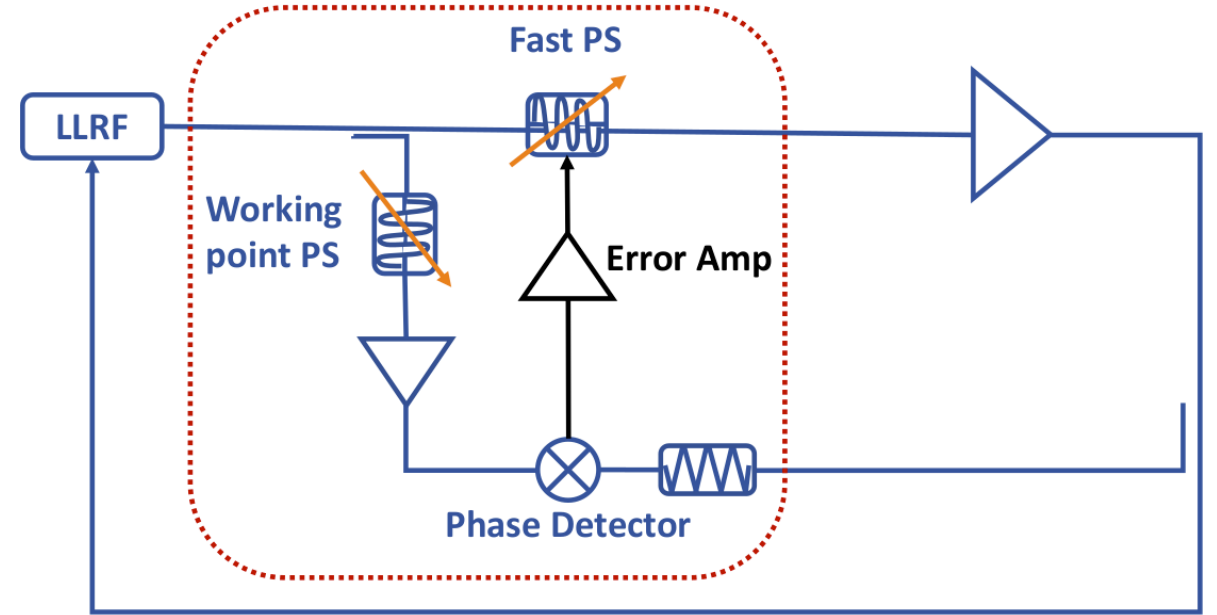
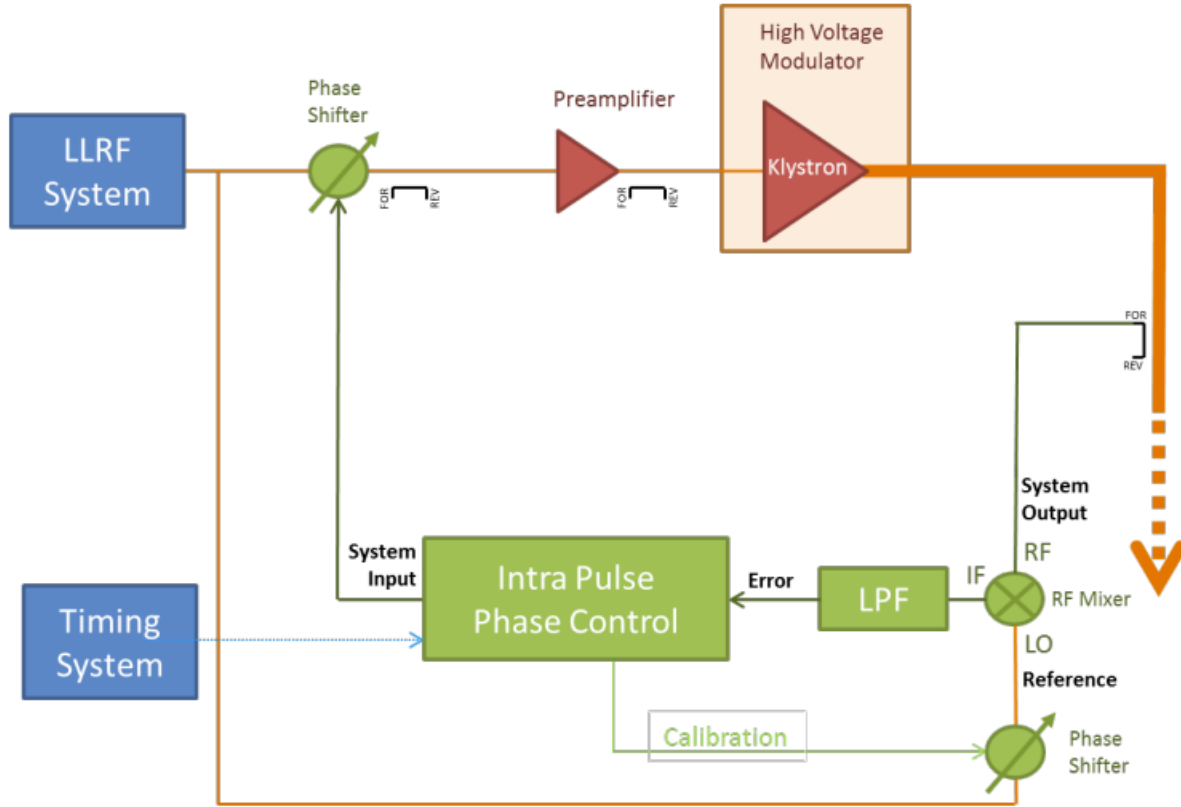
Short-pulse electron LINACs, typically operating with RF pulses below $10\ \mu\text{s}$, generally adopt **pulse-by-pulse LLRF control**.



Intra-pulse Feedback Concept



Review of existing concepts



[1] Intra Pulse Phase Control, Manuel Brönnimann, PSI, LLRF Workshop 2015

[2] Upgrade of the fast analogue intra-pulse, phase feedback at SPARC_LAB,
Luca Piersanti, INFN LNF, LLRF Workshop 2023

Existing concepts: Klystron jitter is measured relative to the **phase-shifted drive signal**.

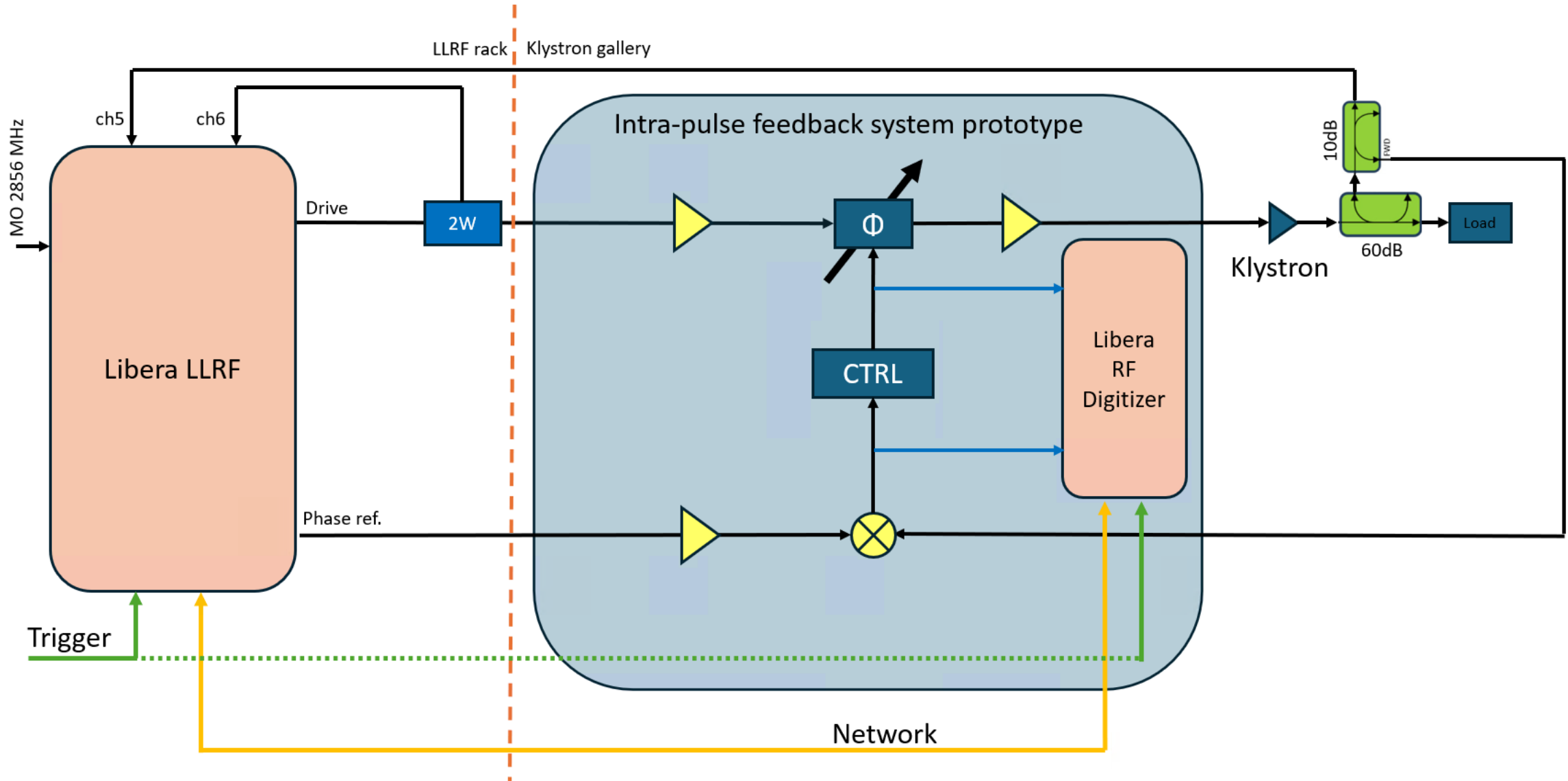
New approach: Independent **phase reference** enables flexible working-point selection and effective intra-pulse feedback

Outline

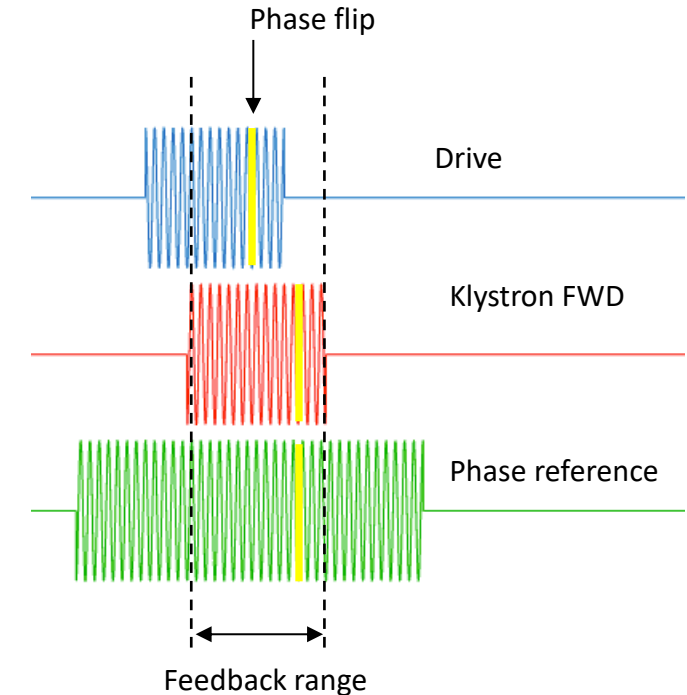
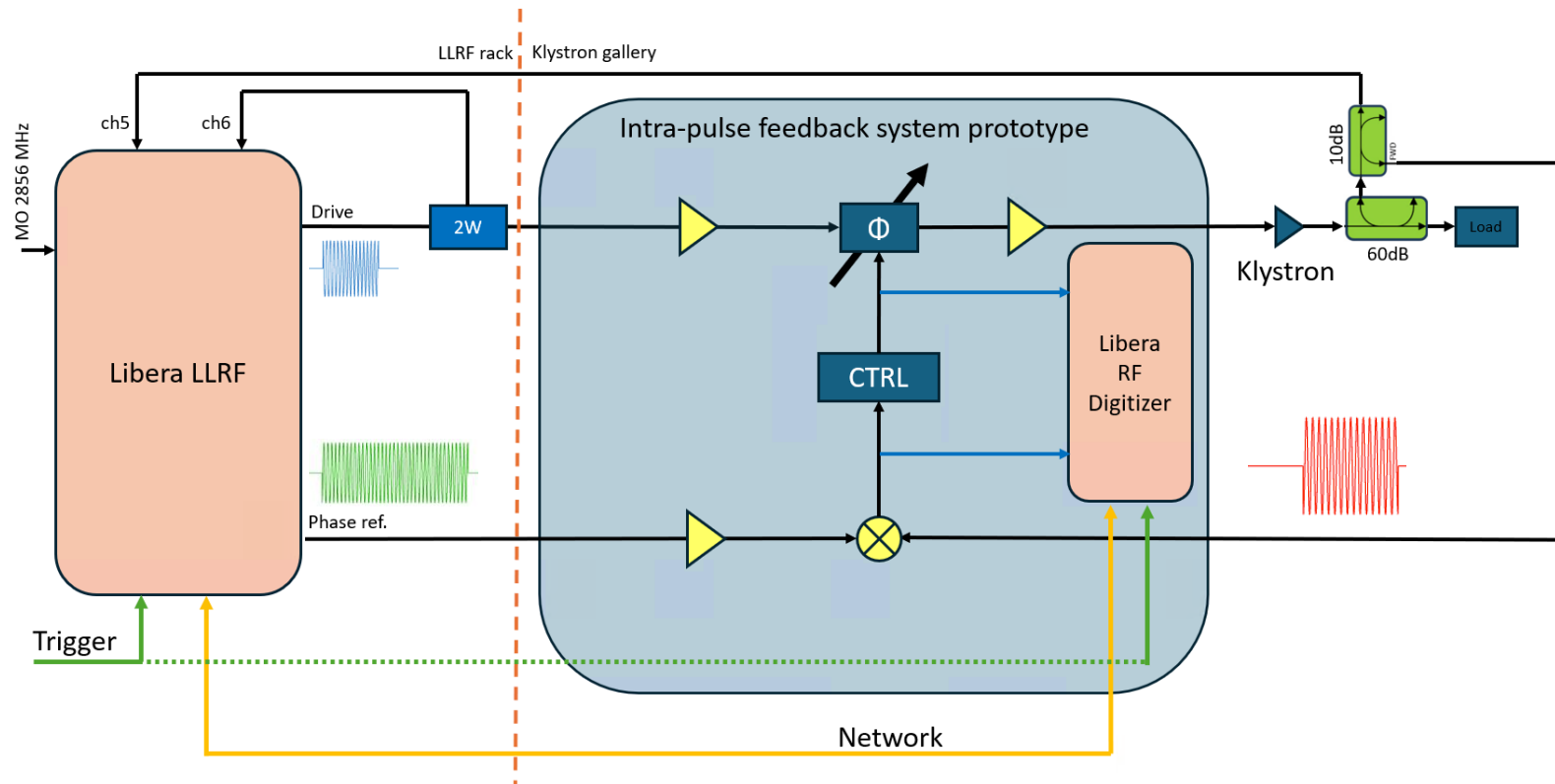
- Introduction to LLRF systems
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The phase-reference-based intrapulse feedback prototype



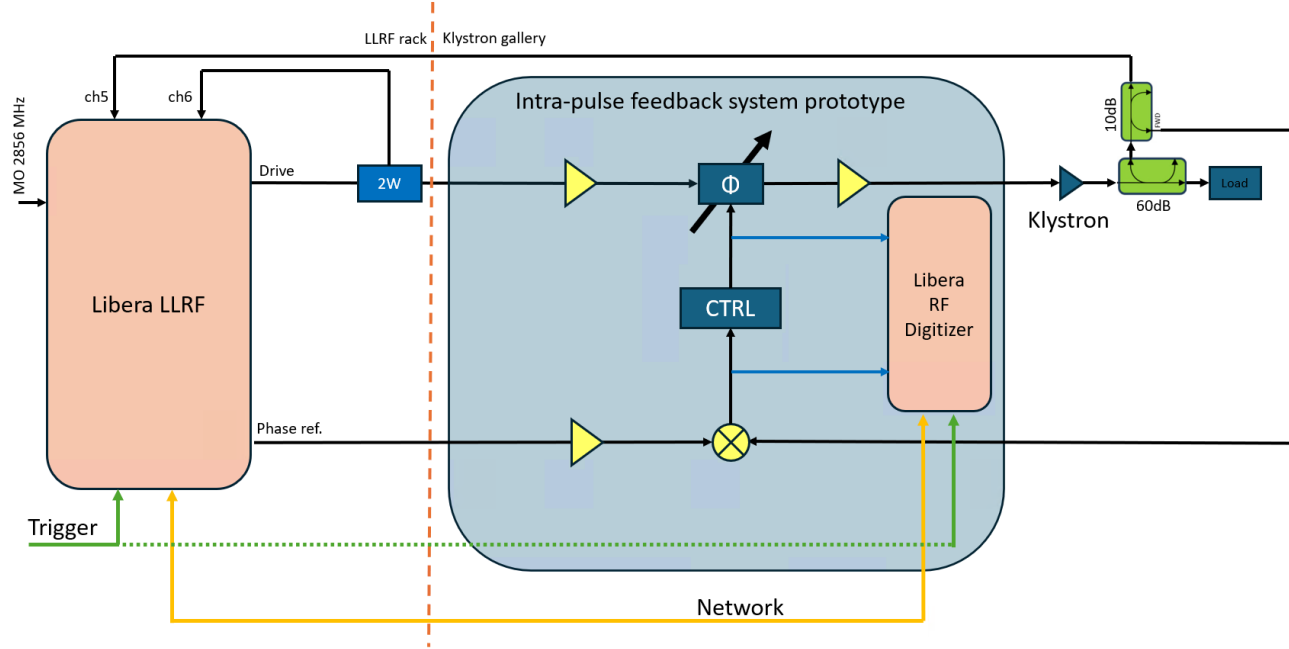
Key Features of phase referenced IntraPulse Feedback



- **Automated setup and calibration:** reduces manual adjustments and simplifies commissioning.
- **Advanced high-power RF diagnostics:** provides detailed insight into high power RF system performance.
- **Short-pulse feedback:** phase reference available before the klystron pulse, avoiding propagation-delay limitations.
- **Pulse shaping and phase modulation:** enables feedback on shaped and rapidly modulated pulses (e.g. SLED/BOC pulse-compression systems) by applying the required phase profile and timing to the phase reference.

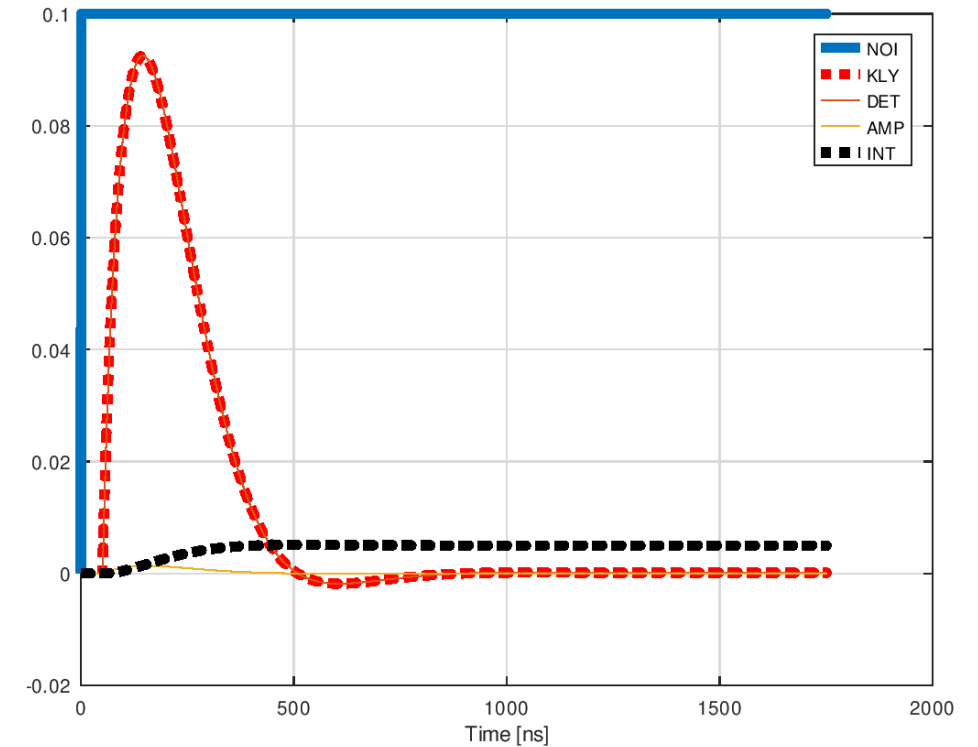


Intra-pulse feedback system prototype design

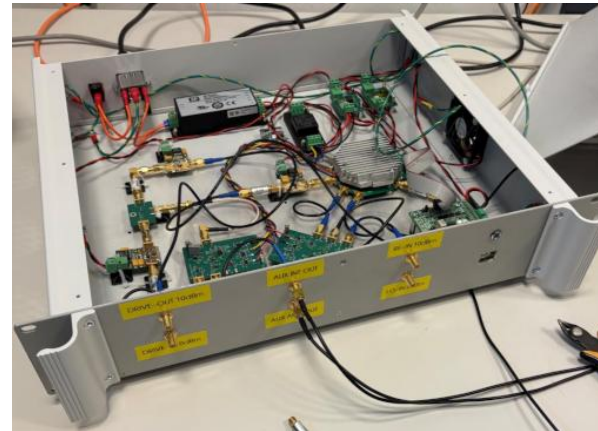


Closed loop modelling for a 0.1 deg phase step:

- Klystron bandwidth: 10 MHz
- Group delay: 82 ns
- Settling time: < 500 ns



- RF frequency: 2856 MHz
- Custom designed Phase shifter:
 - High bandwidth design: > 25 MHz
 - Low PM-to-AM conversion
- Control type: Limited-gain integrator
- Loop switch
- Loop gain adjustment
- Working point configuration



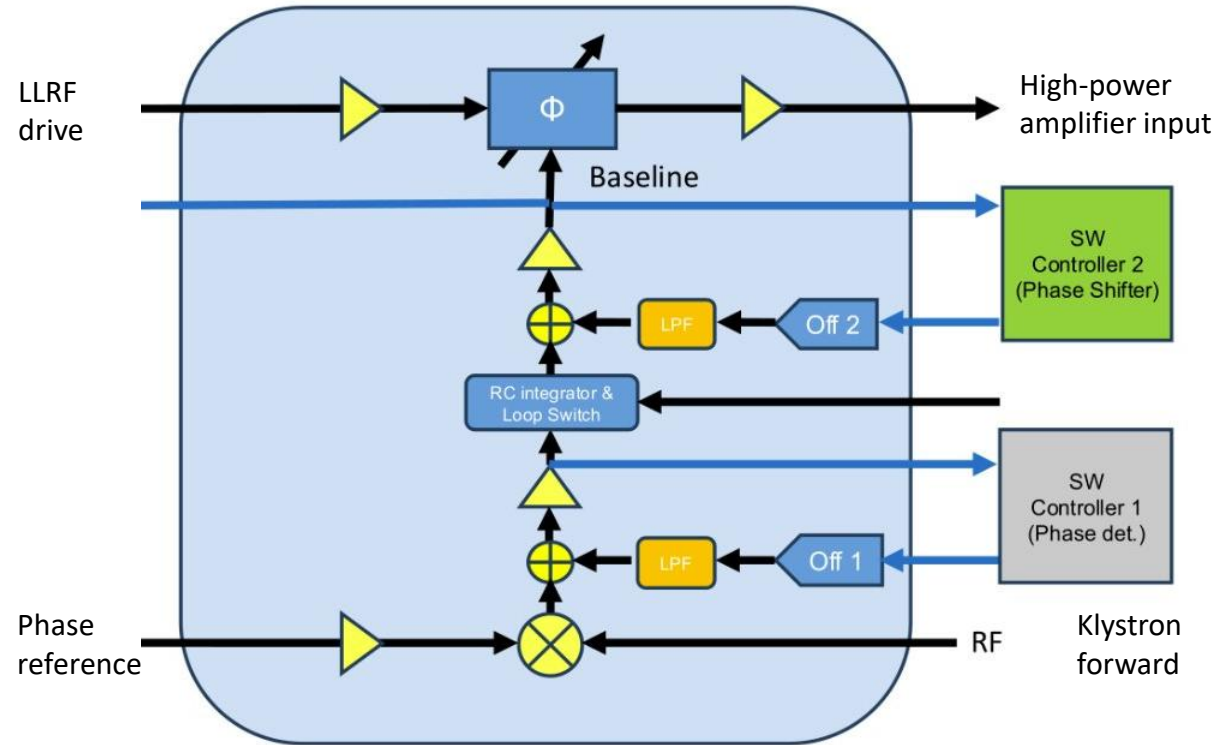
The phase-reference-based Intra-Pulse feedback prototype



The Intra-Pulse feedback prototype and the Libera RF Digitizer used for the diagnostics.



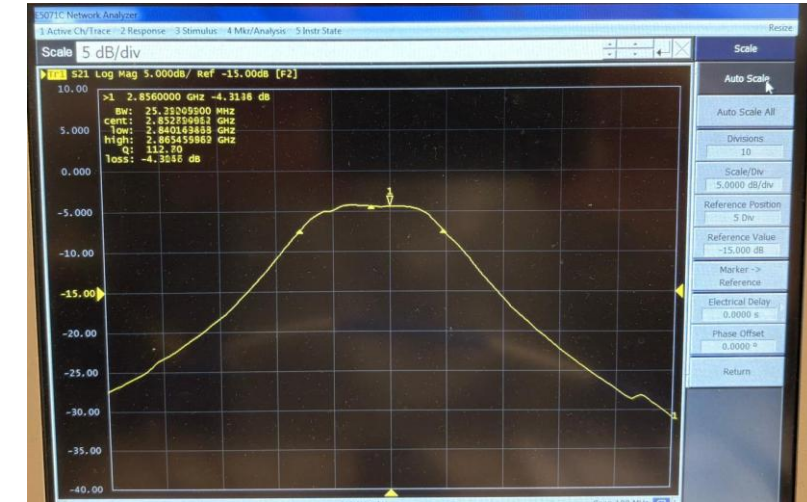
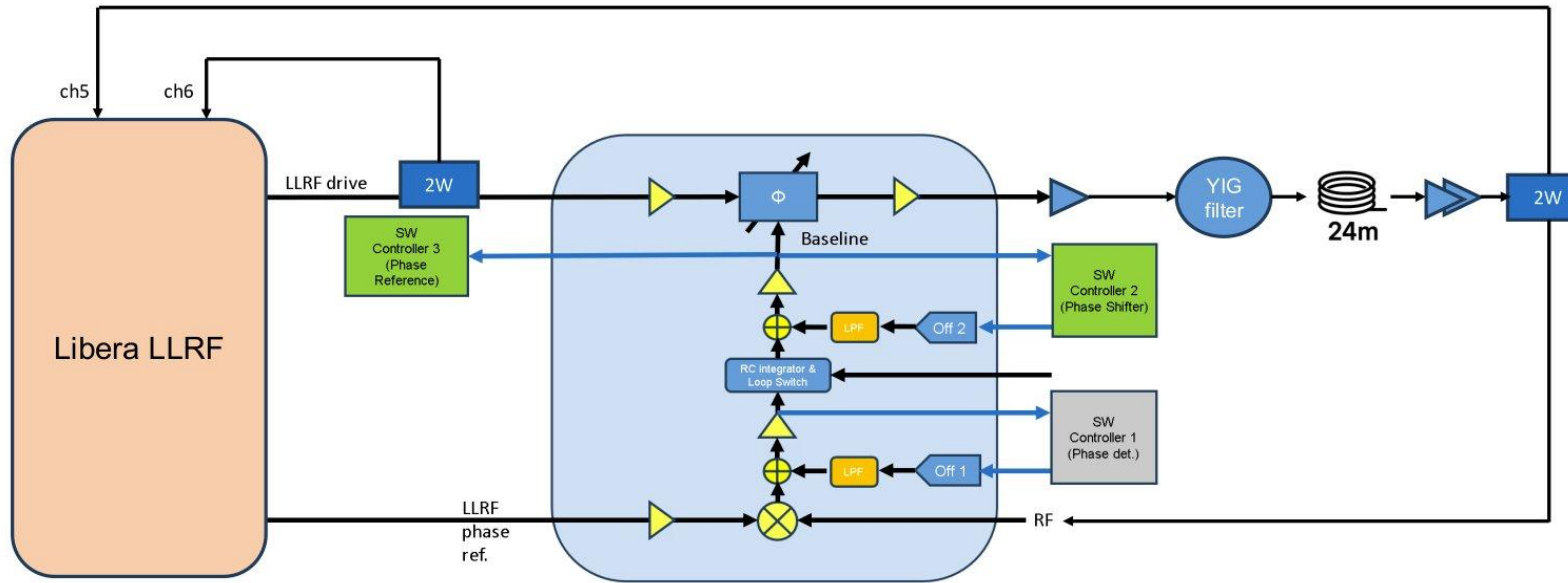
Prototype Architecture & Functionality



- Feedback loop characterization and gain adjustment
- Real-time feedback loop diagnostics
- Automatic quadrature working-point setup and tracking
- Phase-shifter working-point configuration and tracking
- SLED phase-flip configuration and phase-reference synchronization
- Pulse-by-pulse amplitude and phase control
- RF system diagnostics

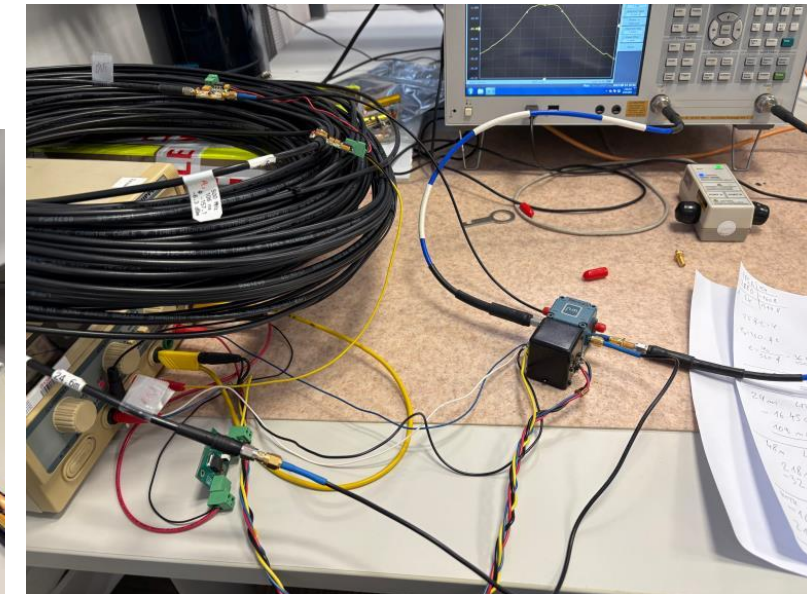
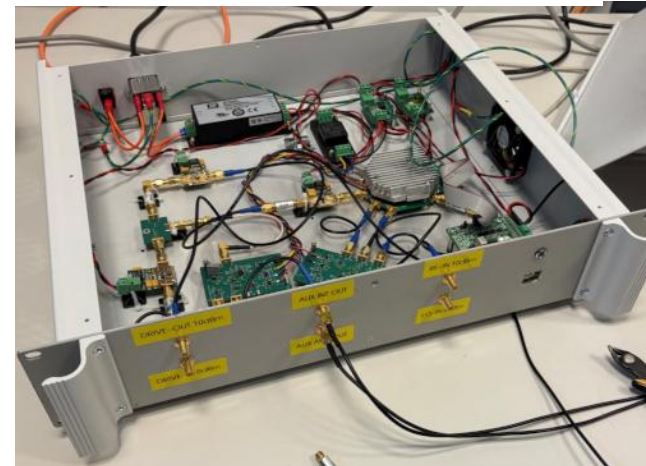


Laboratory characterization



Modelling klystron response in laboratory:

- RF cable 24 m, group delay ~ 120 ns
- YIG filter: 25 MHz BW
- Adding external source of noise to simulate the jitter
- Laboratory results: STD over 600 pulses (60 s)
 - Open loop: 0.102 deg RMS
 - Closed loop: **0.008 deg RMS**



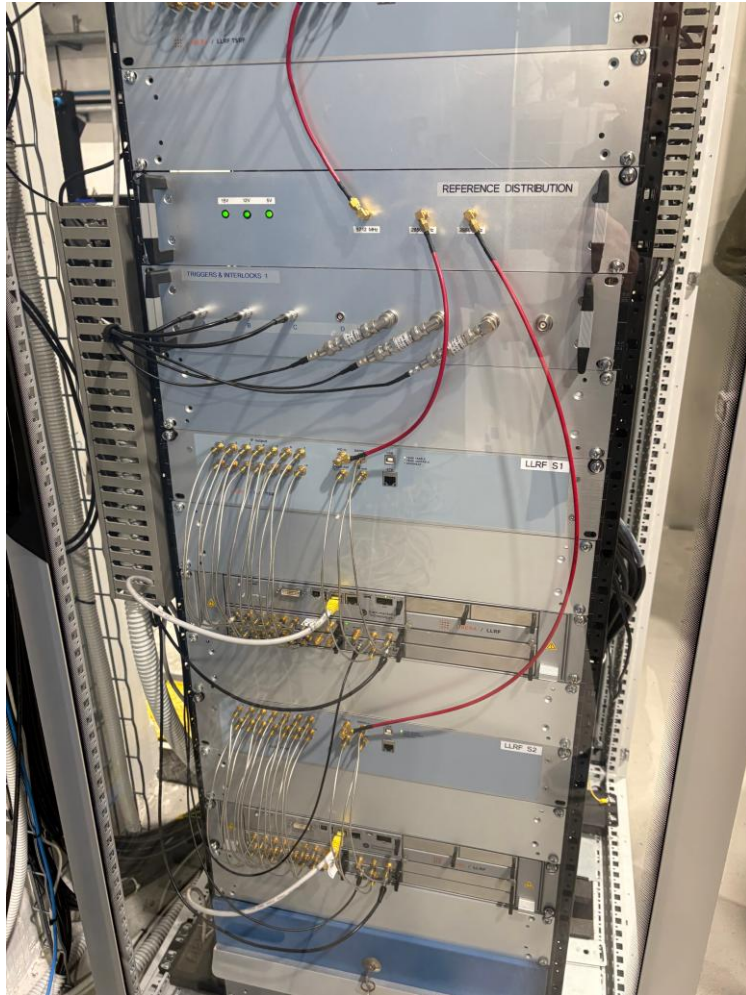
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SPARC-Lab testing (INFN Frascati)

SPARC-Lab LLRF rack



40 m

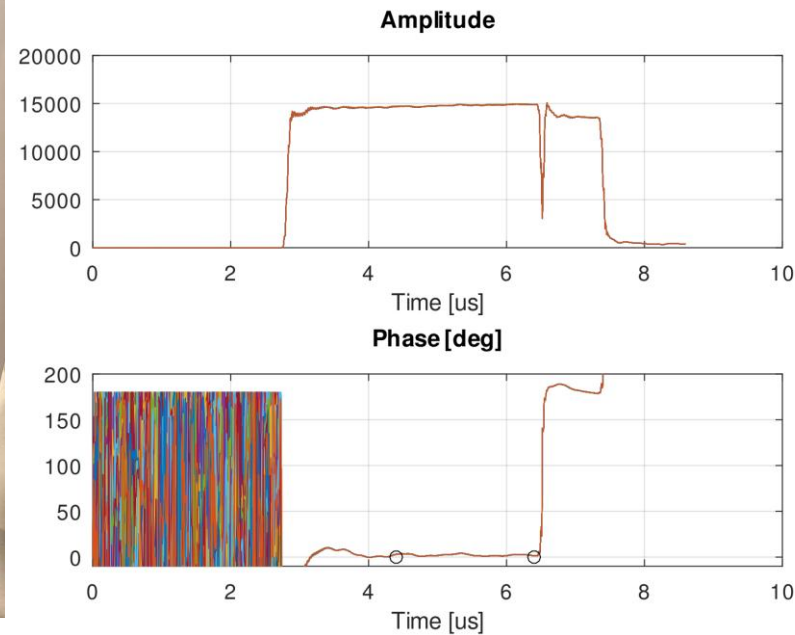
SPARC-Lab Klystron gallery



Main testing parameters:

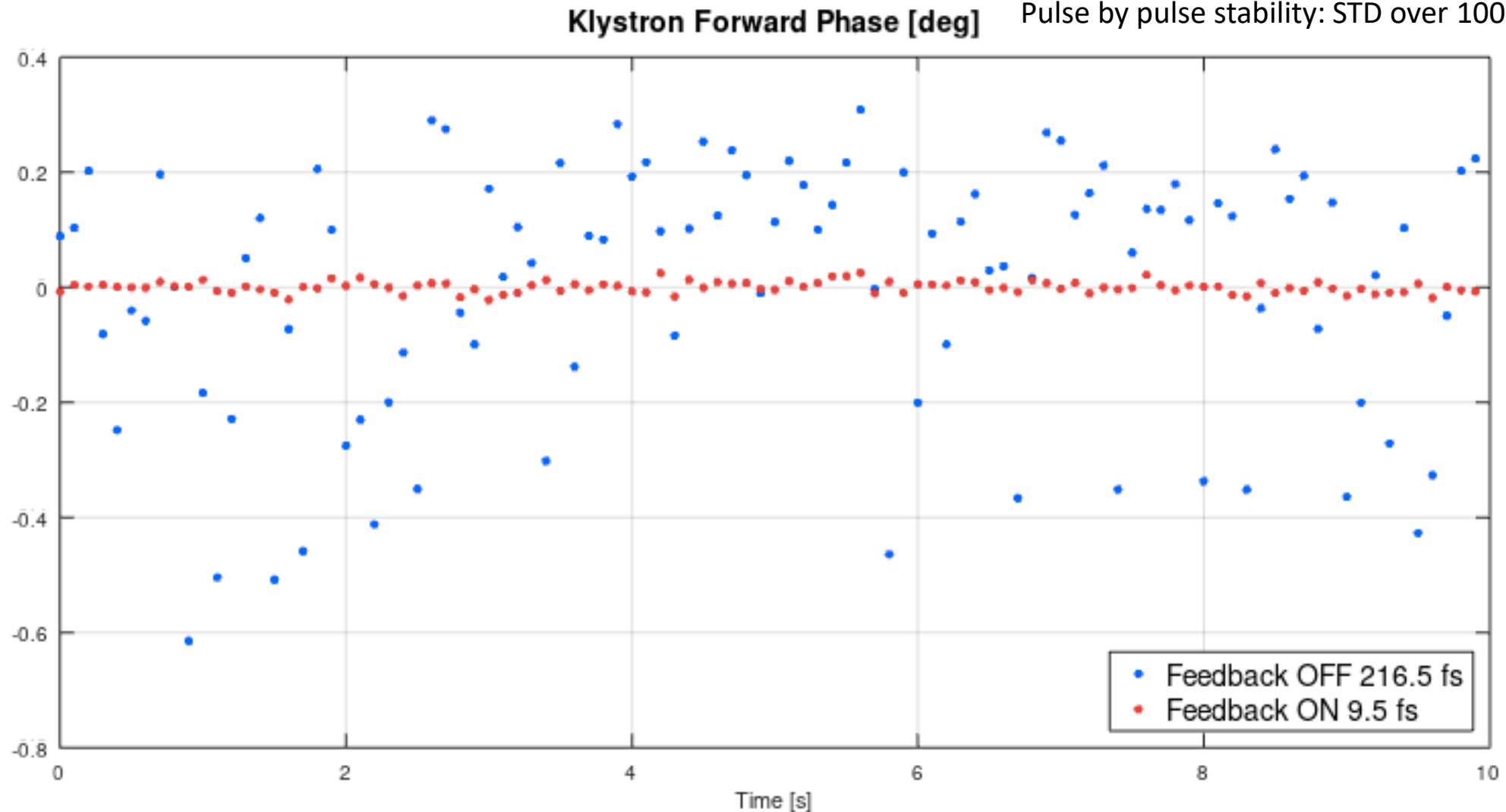
- RF frequency: 2856 MHz
- RF pulse: 4.5 μ s
- 10 Hz rep. rate
- Klystron power: $\sim$ 20 MW (not saturated)
- SLED phase flip: last 0.9 μ s

Klystron forward signal:



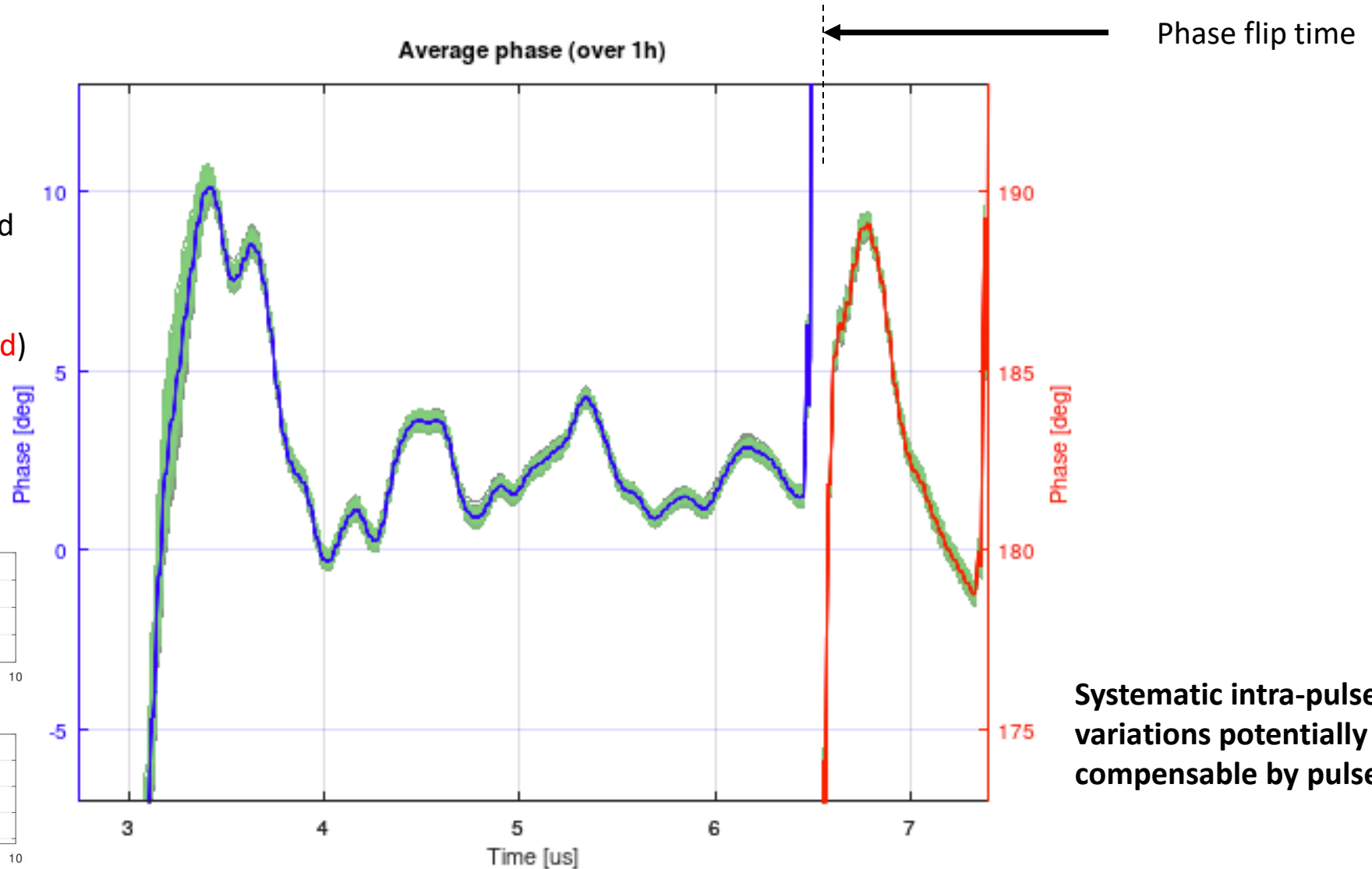
Open vs. closed loop performance

Pulse average 4 μ s to 6.5 μ s (before phase flip)
Pulse by pulse stability: STD over 100 pulses (10 s)



Long-Term Phase Residual Analysis: 60 min acquisition

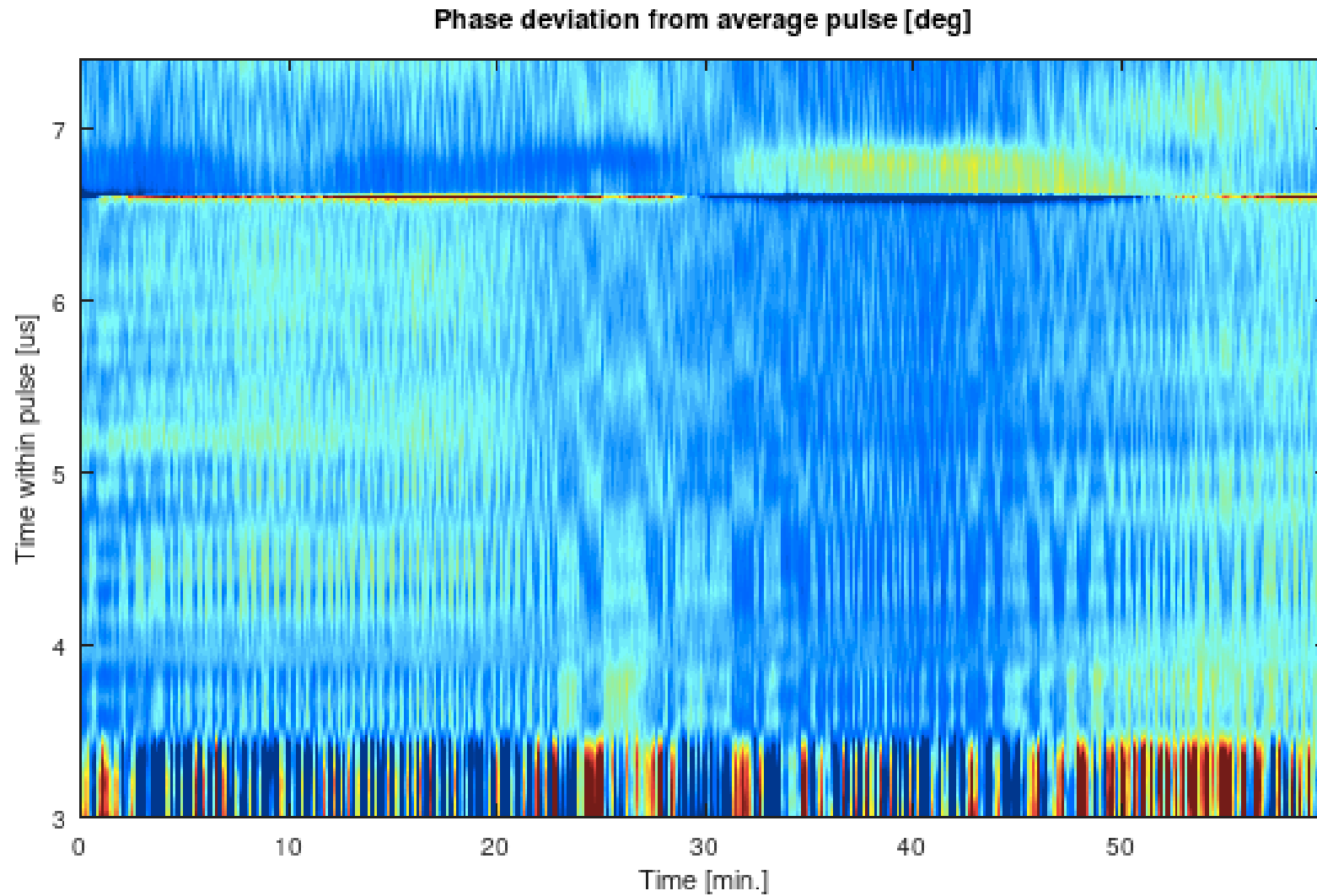
- Klystron forward phase
- RF pulse: 4.5 μs
- SLED phase flip: last 0.9 μs
- 10 Hz rep. Rate
- Klystron power: ~ 20 MW
- Intrapulse feedback enabled
- **36000 pulses, 60 minutes**
- Average phase (blue and red)
- Individual pulses (green)



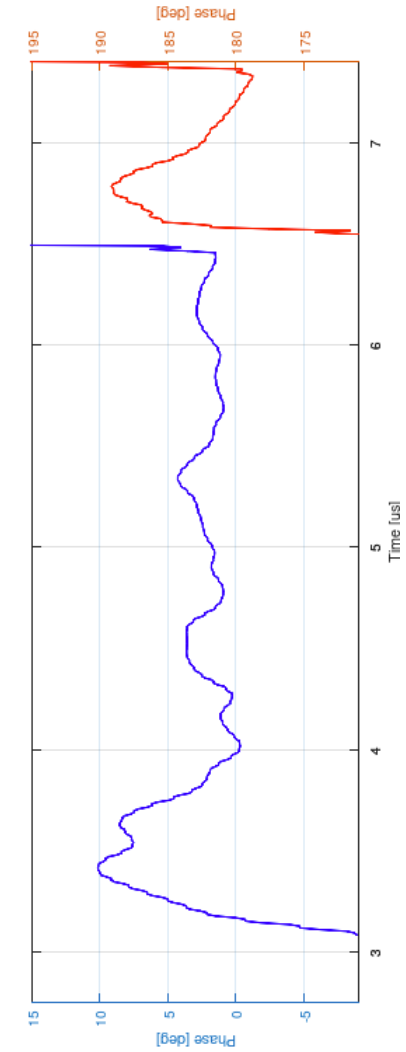
Systematic intra-pulse phase variations potentially compensable by pulse shaping



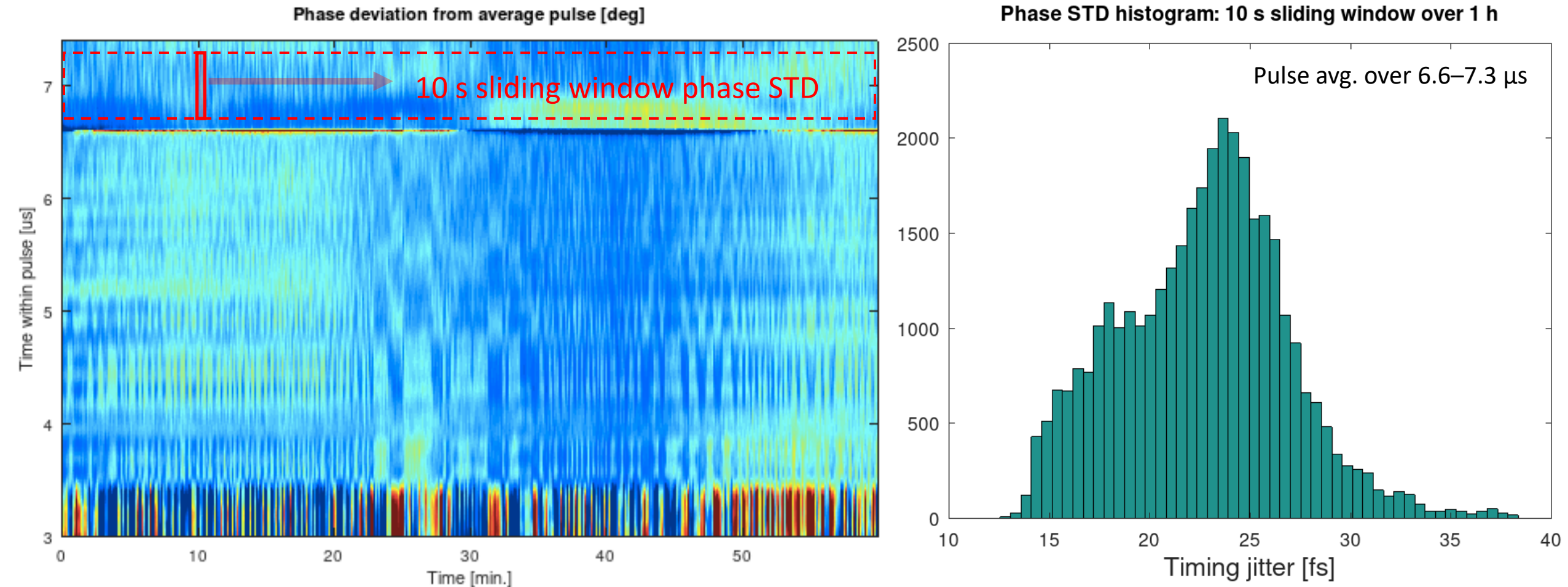
Long-Term Phase Residual Analysis: 60 min acquisition



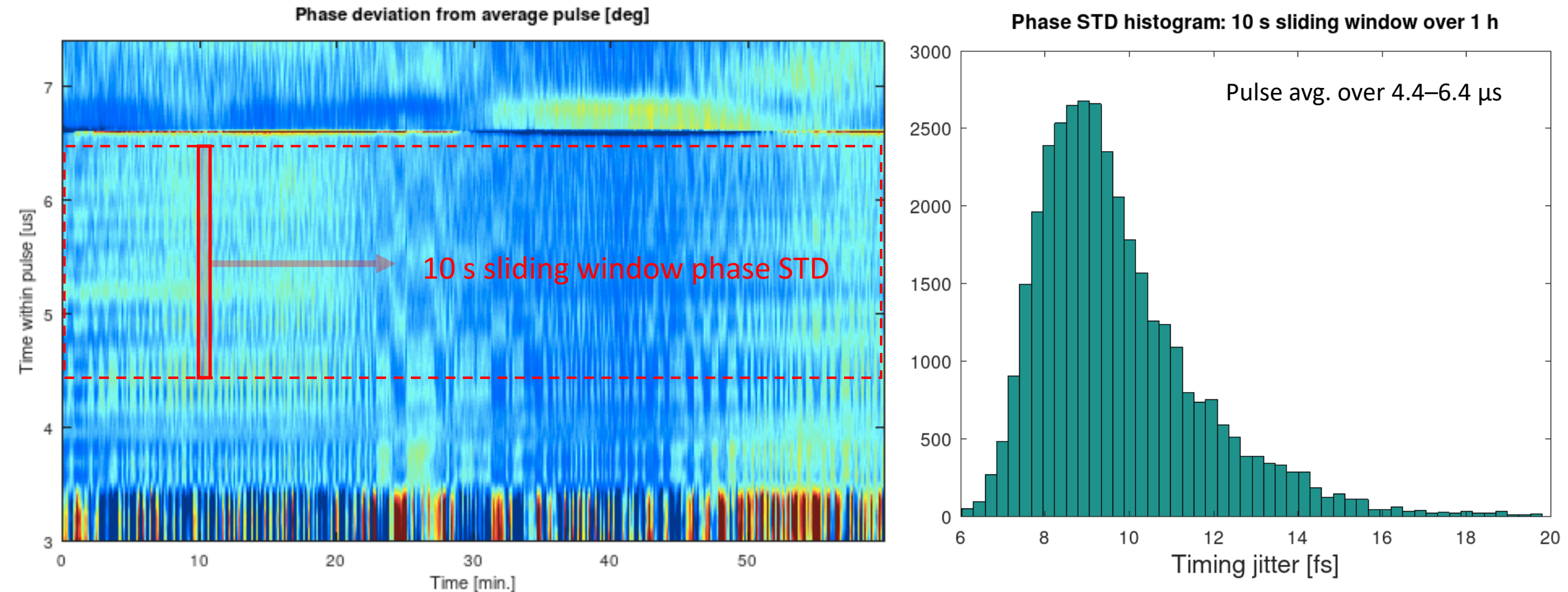
Average pulse phase



Long-Term Phase Residual Analysis: 60 min acquisition



Long-Term Phase Residual Analysis: 60 min acquisition

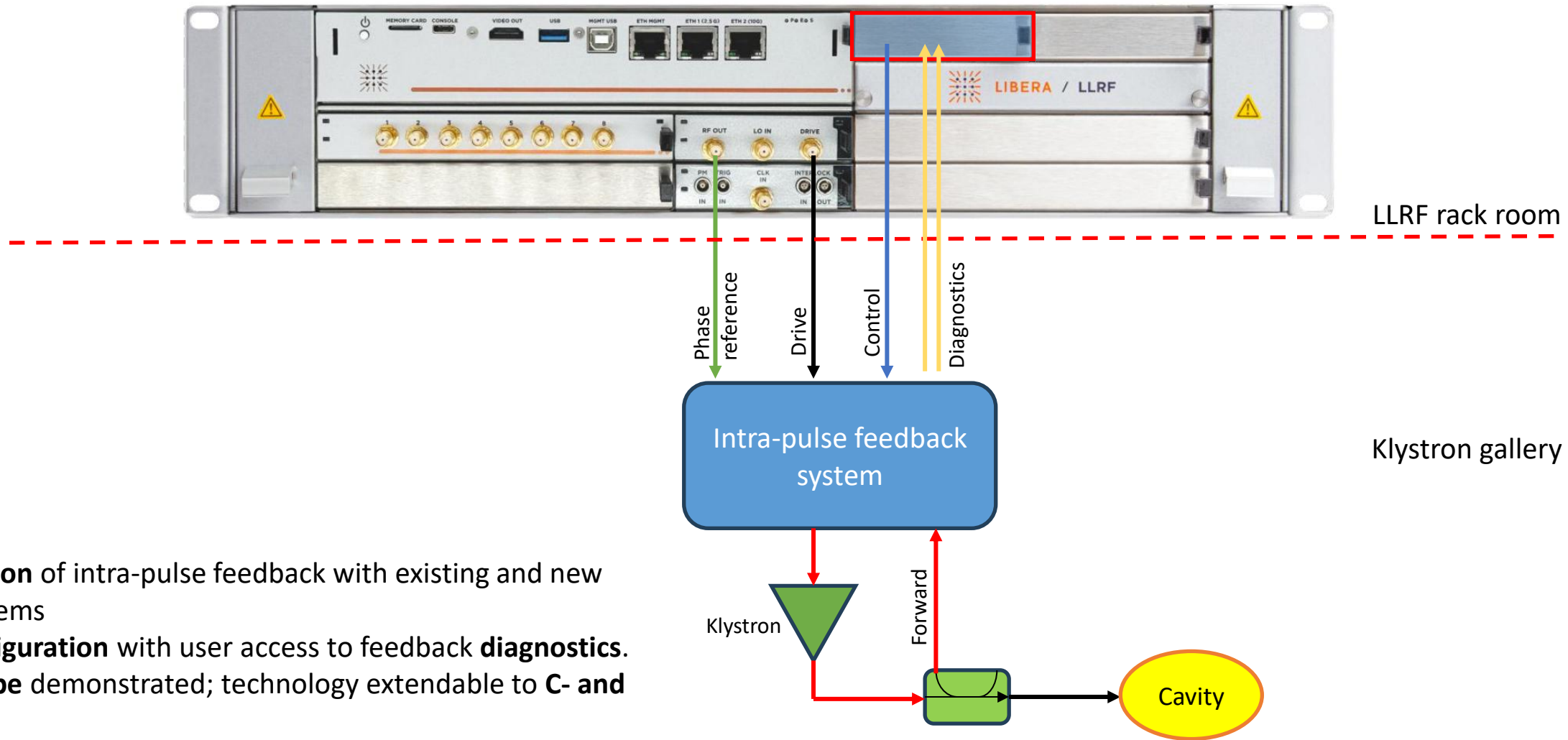


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Libera LLRF upgrade with the intra-pulse feedback system



- **Simple integration** of intra-pulse feedback with existing and new Libera LLRF systems
- **Automatic configuration** with user access to feedback **diagnostics**.
- **S-band prototype** demonstrated; technology extendable to **C- and X-band**.



Conclusions



- **Promising first field results at SPARC-Lab:** intra-pulse feedback reduced RF phase jitter from **216 fs to 9.5 fs**.
- Further improvement might be achieved by compensating **systematic phase variations along the RF pulse** using the RF pulse shaping functionality.
- The concept is scalable to **other RF frequencies**, including C-band and X-band applications.
- **Next step:** integrate the phase-reference approach as an extension of the Libera LLRF product
- **Integration of the intra-pulse feedback** into Libera LLRF would simplify deployment and operation through automated configuration, enabled by the phase-reference-based architecture.
- **Special thanks to Dmitry** for the valuable discussions and collaboration, and to the **INFN-LNF RF Group at SPARC-Lab** for their support and the opportunity to perform the measurements.

THANK YOU FOR YOUR ATTENTION!