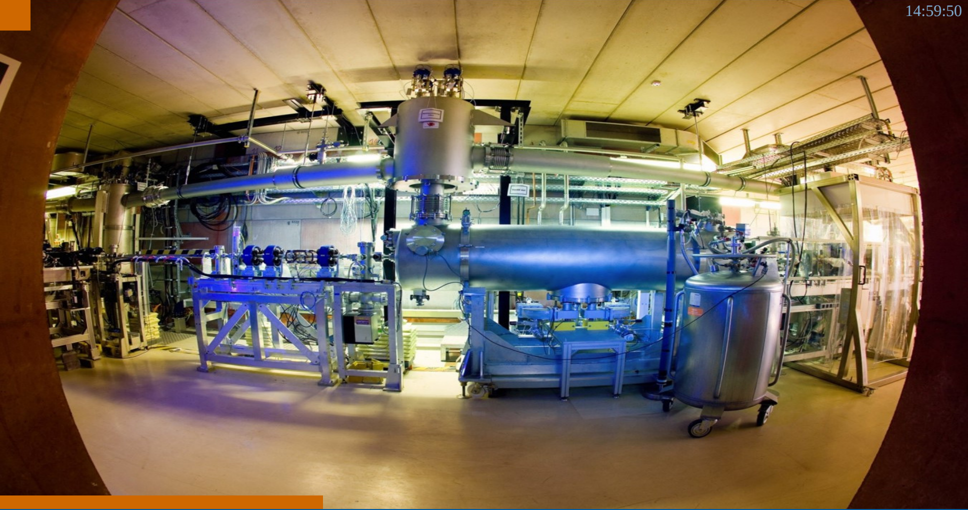


Digital LLRF at ELBE: Performance and first impressions of user operation

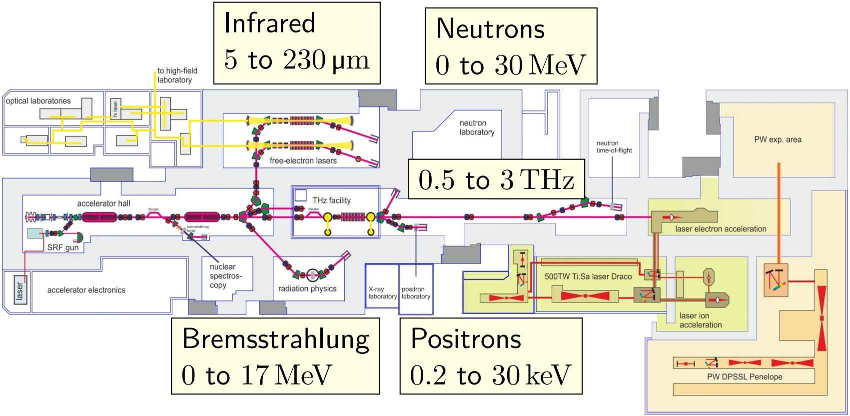
Klaus Zenker, ARD ST3 Workshop, 24.09.2020

HZDR

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

ELBE – Center for high power radiation sources

e^- flow since almost 20 years



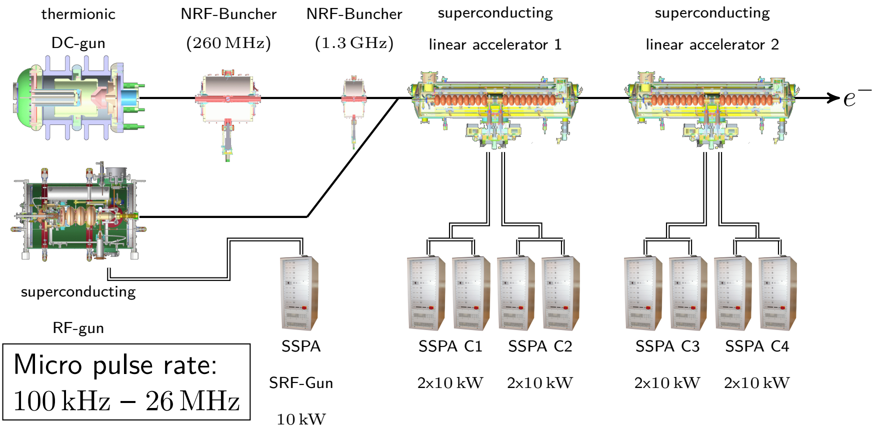
Characteristic:

- Multi-source facility
- Pulsed and CW mode operation

Example beam parameter:

- Beam energy: $8\,\mathrm{MeV}$ to $40\,\mathrm{MeV}$
- Average beam current: $1600\,\mu\mathrm{A}$

Accelerator

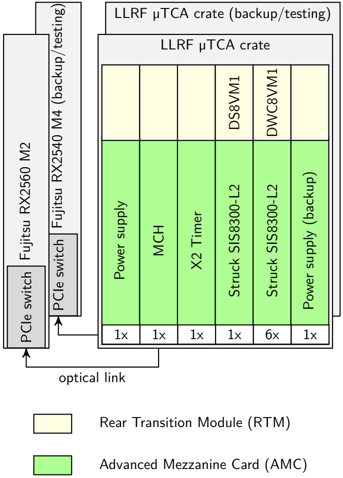


Micro pulse rate:
100 kHz – 26 MHz

Cavity powering at ELBE

Individual SSPAs allow single cavity control in cw mode!

Components of the digital LLRF at ELBE



Hardware:

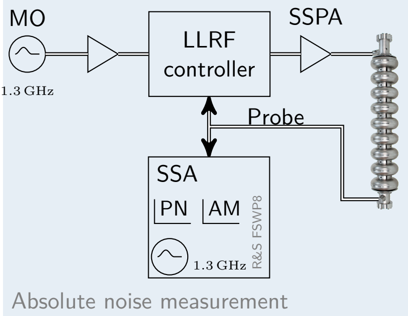
- Master oscillator: $1.3\,\mathrm{GHz}$ (REF), $260\,\mathrm{MHz}$ (REF), $78\,\mathrm{MHz}$ (CLK)
- UniLOGM: $8\times$LO ($1.3\,\mathrm{GHz}+54^1/_6\,\mathrm{MHz}$), $8\times$CLK ($65\,\mathrm{MHz}$), $8\times$REF ($1.3\,\mathrm{GHz}$))

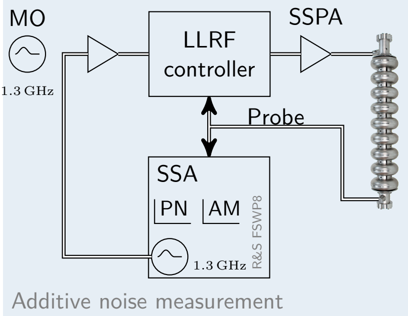
Software:

- Firmware for struck boards ⇒ LLRF controller (adopted for cw operation in collaboration with DESY)
- Control software for the LLRF ⇒ ChimeraTK (together with DESY)
- Adapter for ChimeraTK that is compatible with WinCC ⇒ OPC-UA Adapter (TU Dresden, now IOSB Karlsruhe)

Out of loop measurement of Amplitude Modulation and Phase Noise

Out of loop: Measurement of the probe signal with respect to the internal reference of the signal source analyser.

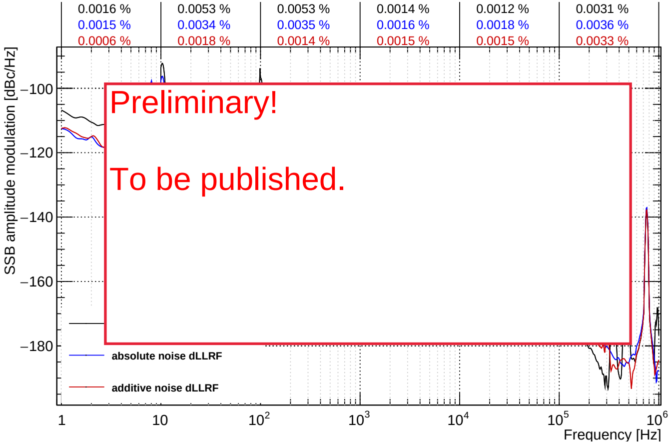




- Includes all noise sources in the control loop
- Excludes noise from the master oscillator

Noise measurements

SRF cavity amplitude modulation (gain: 40, $6\,\mathrm{MV}$)

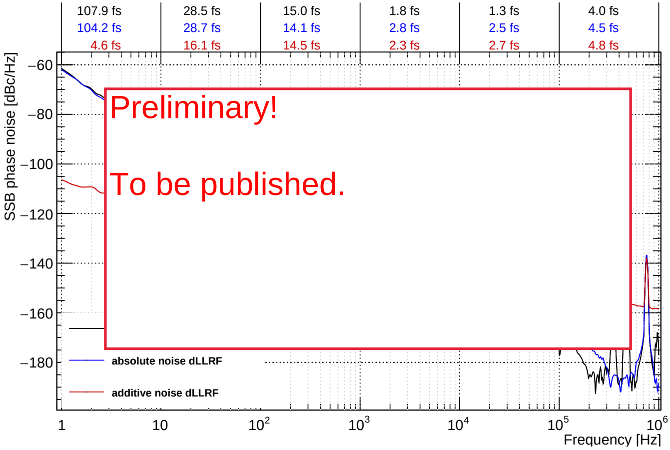


- Int. abs. AM: $0.0066\,\%$ (dLLRF), $0.0085\,\%$ (aLLRF)

$\Rightarrow$ $< 0.01\,\%$ (TARLA/MESA requirements)

Noise measurements

SRF cavity phase noise (gain: 40, $6\,\mathrm{MV}$)



- Int. abs. PN: $113\,\mathrm{fs}$ (dLLRF), $109\,\mathrm{fs}$ (aLLRF)

$\Rightarrow$ additional noise of $23\,\mathrm{fs} \rightarrow 0.01°$ (TARLA/MESA)

Longterm drifts

Observation:

- Already when the aLLRF is operated a drift of the amplitude/phase signals is observed with the dLLRF system
- The drift correlates with the temperature in the dLLRF rack

⇒ Peak-to-peak temperature oscillation of $1\,\mathrm{K}$ introduced by the rack cooling

Reference tracking

Idea:

- Measure the reference signal with the dLLRF system
- Assumption: Reference amplitude and phase are stable
- Use changes seen on the reference signal to correct probe, forward and reflected signals

⇒ Compensate temperature/humidity changes in the dLLRF rack

Reference Tracking

- Improved energy stability reduced from $\frac{\delta E}{E} = 0.3\,\%$ to $0.05\,\%$
- Caused by cooling water temperature oscillations

On the way to user operation

Solved issues:

- Attenuator setting
- Controller design
- Broken connections to the SCADA system (WinCC)
- System calibration with respect to the aLLRF
- Limiter configuration
- Modification of the ramp up procedure

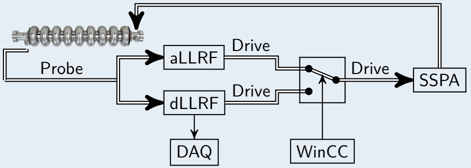
Optimized ramp up procedure:

- Ramp in closed loop
- Update OVC during ramping

Improved machine protection:

- Forward firmware state to the machine protection via front panel AMC outputs
- Use additional limiter on the VM signal to introduce intrinsic safety functionality (independent of the probe, forward, reflected signals that could be disconnected)

User operation



Overview:

- Since August 2020 all ELBE beam paths/experiments were operated using the dLLRF
- Settings were prepared for aLLRF and dLLRF
- Turned out to be most practical to prepare the setting using the aLLRF and than switch to dLLRF $\Rightarrow$ just takes a few minutes
- Probe read back values can be used to setup the dLLRF while aLLRF is in operation $\Rightarrow$ the machine is in the exact same state after switching to dLLRF
- Switching from dLLRF to aLLRF is not that straight forward (mechanical phase shifter, remaining controller error)

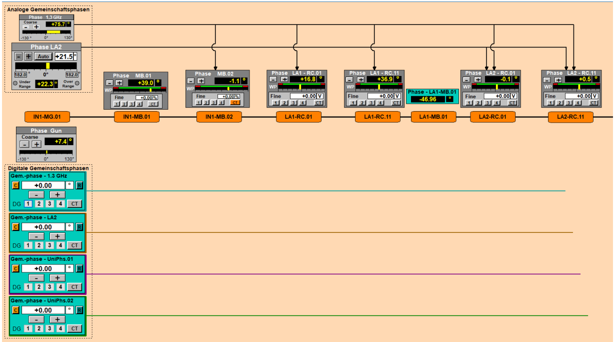
Issues during user operation

$1.3\,\mathrm{GHz}$ phase shifter:

- Affected the 1.3 reference amplitude used by the dLRLF (aLLRF is not sensitive to amplitude changes)
- Problem for the reference tracking

$\Rightarrow$ Removed this phase shifter from the dLLRF path

- Implemented a virtual phase shifter + arbitrary virtual phase shifter by combining different phases (e.g. LA2 phase)



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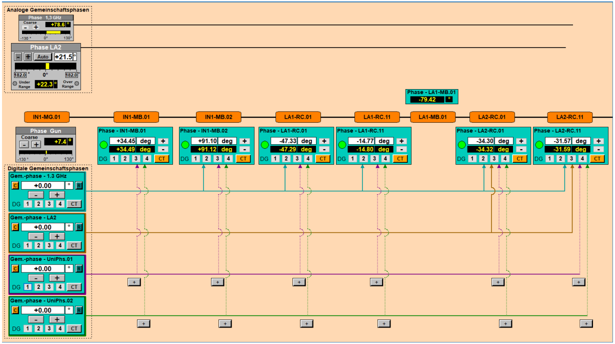

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Reference tracking:

- Remaining energy drift is seen on the BPMs and e.g. FEL power
- For some beam paths we can activate an energy stabilization based on the BPM position measured in a dispersive section ⇒ not possible for all beam paths

LLRF trigger bind to the marco pulse:

- In combination with the with SRF gun (should only be operated at $5\,\mathrm{Hz}$ in macro pulse mode) slow operation of the dLLRF

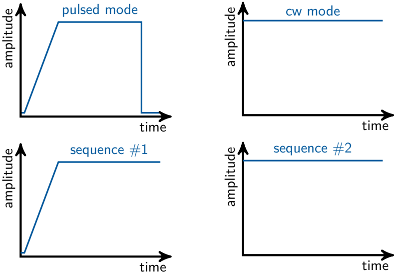
⇒ Will be solved with the new timing system that is under development (COSYLAB)

Future features

1. Measure the cavity detuning in cw mode
   - Andrea Bellandi (DESY) is implementing a dedicated algorithm in the LLRF firmware
   - First tests at ELBE were done $\Rightarrow$ The algorithm is not yet ready
2. Advanced Beam Based Feedback
   - See talk by Andrei Maalberg
3. Second tone based drift compensation
   - Once available at DESY
4. Improve ramp up procedure
   - Use table sequence to speed up ramping
   - Possibly compensate detuning during ramp up via phase rotation $A \sin(\omega t) \rightarrow A \sin(\omega t + \phi(t))$

cw mode rampup using table sequence

- Currently we update the setpoint with every macro pulse $\Rightarrow$ steps need to be small enough to not trigger a window interlock and the maximum macro pulse rate is $25\,\mathrm{Hz}$
- Combine two tables in a sequence to ramp up in cw mode



- Using a table sequence allows to ramp up the cavity field way faster
- Table sequences in combination with a firmware based detuning compensation via a phase rotation would be most useful for SRF gun operation (significant Lorentz force detuning)

$\Rightarrow$ This requires a change of the firmware

Summary

Digital LLRF at ELBE:

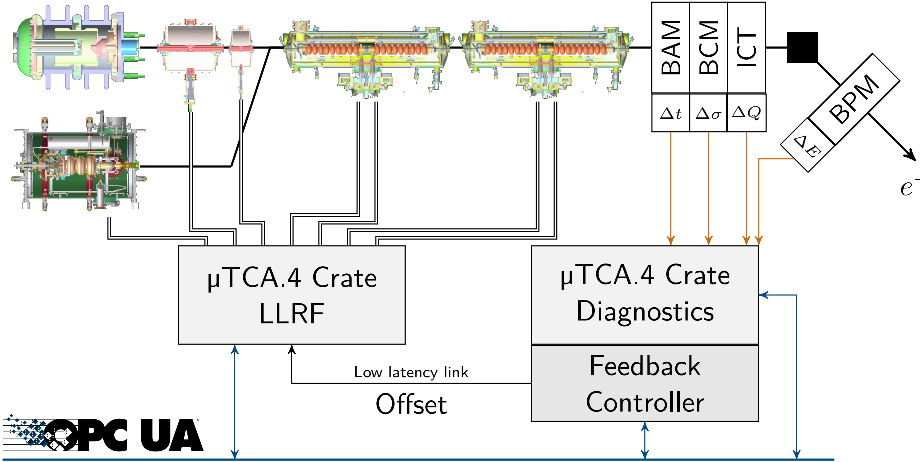
- In user operation since August without major problems
- First cw machine using the MicroTCA based digital LLRF system
- Huge improvement in terms of system flexible compared to the previous analogue system
- Performance of the dLLRF is good and meets requirements of future cw machines like MESA and TARLA
- We demonstrated a possible implementation for DALI

Acknowledgements:

- We thank DESY for the close collaboration in firmware and software development and general support.

Backup

Beam based feedback



- Diagnostic crate design and firmware
- ChimeraTK diagnostics application
- Feedback controller

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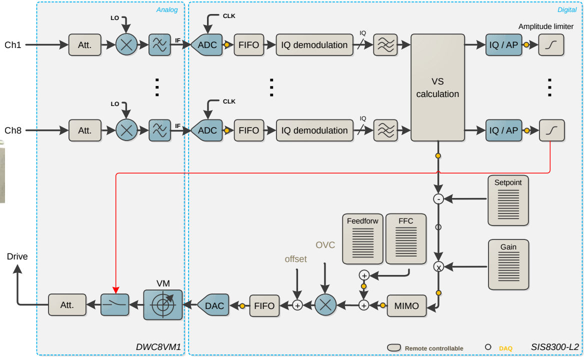
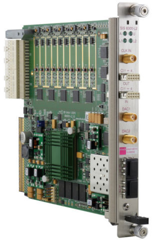
LLRF controller



[Chr. Schmidt]



- Per cavity/buncher: forward, reflected, probe, reference are sampled
- Control loop is based on vector sum signal $\equiv$ probe signal
- Remote control and DAQ via ChimeraTK LLRF server (developed at DESY)

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Integration into ELBE infrastructure