Efficient LLRF control with AI/ML for iSAS

TA#1, WP 1.1

Scope of this work package:

In order to allow for energy efficient operation of SRF cavities, the LLRF system needs to be enabled to always push the
cavity in any given possible state to the optimum working point with lowest RF power requirement while still preserving highest field stability at the desired setpoint. The latter has mostly impact on arrival time and energy variations of the beam, especially if field variations are given in the injector cryo-modules.

Disturbances to the system can be manifold, but in continuous wave operation most dominantly are unwanted external perturbations as detuning by microphonics, detuning by Lorentz force coupling to field variations caused by e.g. microphonics, transients in beam-loading causing amplitude or phase variations.

In addition to operation like a single pass FEL driver linac, in an ERL Linac environment there are also possible field variations caused by beam losses in the recirulator leading to thus incomplete recovery or velocity mismatches between low energy injected and high energy recovered beam, which leads again to an incomplete recovery in the early cavities of the Linac. All this is usually compensated by RF power overhead to be supplied by the transmitter.

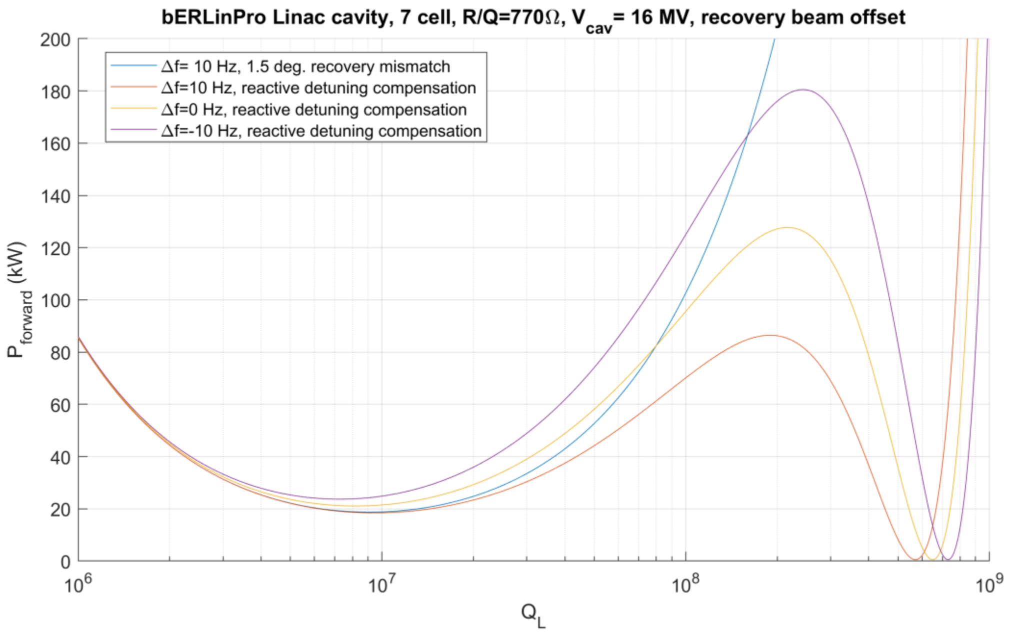
Here, the goal is to demonstrate minimum power requirement. This can be mainly achieved by minimizing the detuning to therefor allow operation at even lower coupling and so higher loaded quality factor, which is usually omitted as the power requirement rises with the detuning over the half-bandwidth squared. Controlling the detuning, be it to compensate microphonics, Lorentz force detuning or reactive beam-loading by countertuning, allows to push the limits of high loaded quality factor operation to higher values.

However, the mechanical response of a cavity towards fast tuners is usually complex, that smarter concepts were developed in the past to integrate the knowledge about the system's physic behavior for e.g. adaptive feedforward
LMS filter controller and similar. This complexity in fast mechanical cavity tuning plus the various operation states, a cavity might have to reach during accelerator beam operation makes it favorable to have a more autonomous system being able to predict and setup the optimal and thus low power consuming working point for the cavity.

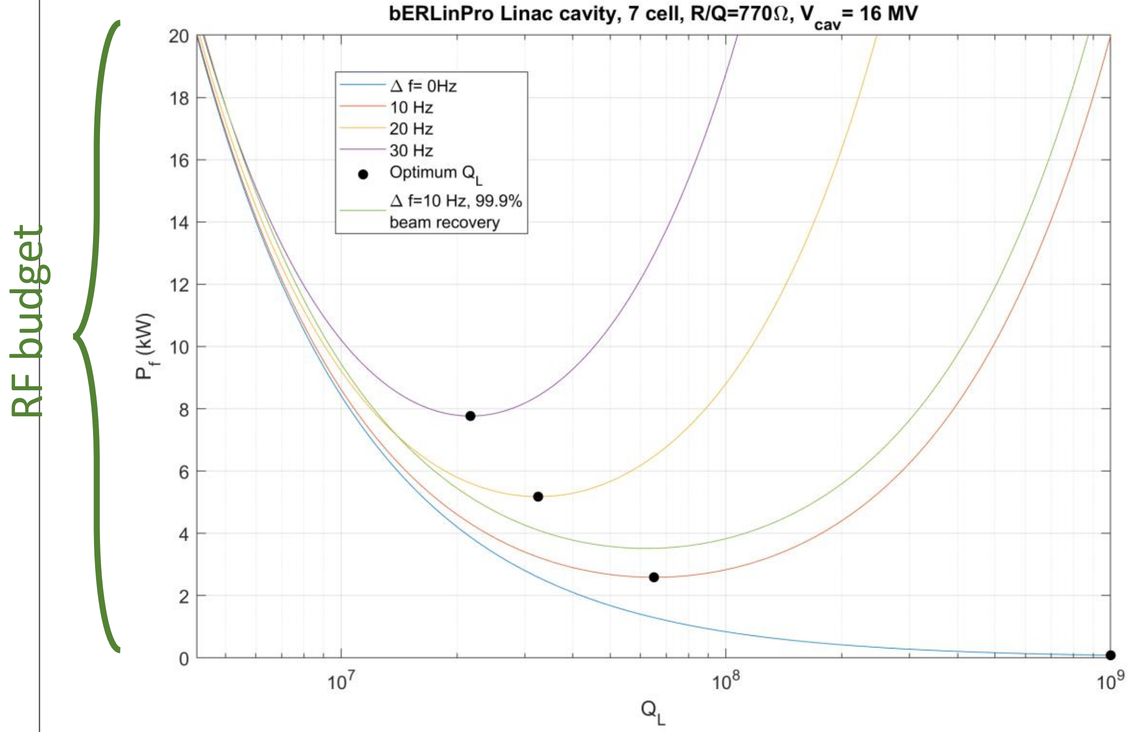
Here, ML/AI methods can come into the game as a virtual operator controlling and setting the sub-systems to the optimum or replacing internal sub-algorithms, as e.g. detuning control, e.g. training neural network?

The problem:

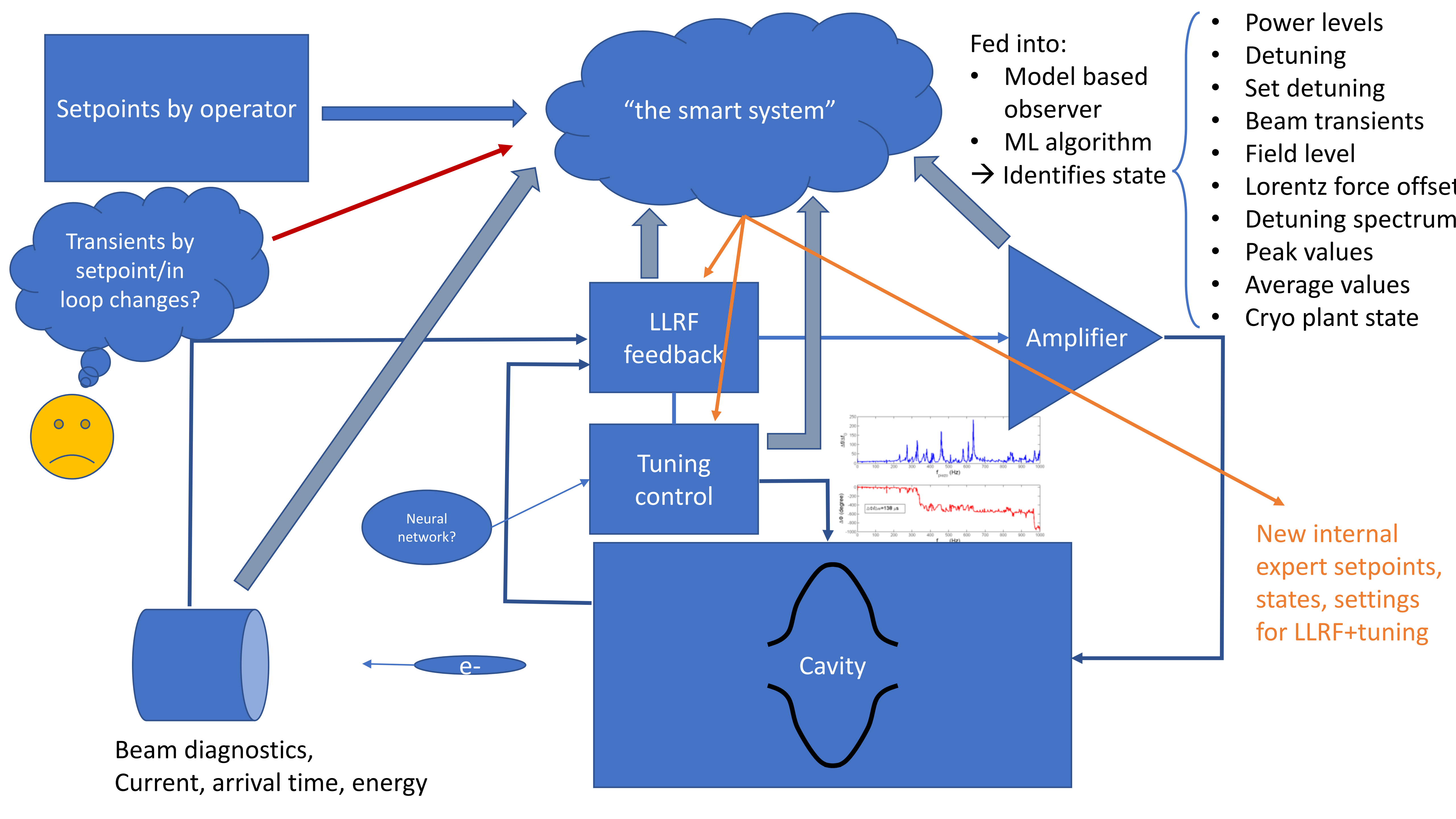
Single pass ERL case, recovery variations mismatch



Single pass Linac case, ERL 100% recovery



The higher the loaded Q, the lower the power consumption given an improved detuning control!
In ERLs, there is also an uncertainty by variations of the recovered beam
→ Control tuning, beam current, arrival time, field level and loaded Q!


Setpoints by operator
"the smart system"
Fed into:
• Model based observer
• ML algorithm
→ Identifies state
• Power levels
• Detuning
• Set detuning
• Beam transients
• Field level
• Lorentz force offset
• Detuning spectrum
• Peak values
• Average values
• Cryo plant state
Transients by setpoint/in loop changes?
LLRF feedback
Amplifier
Tuning control
Neural network?
Cavity
e-
New internal expert setpoints, states, settings for LLRF+tuning
Beam diagnostics,
Current, arrival time, energy

Task group 1:
High loaded Q CW operation

2.5 FTE
Potential Labs.: HZB, DESY, IJCLab, ESS, Lancaster (?)

- Determine the state of the art CW LLRF control at high loaded Q
- Characterization of microphonics detuning and countermeasures
- Define optimal loaded Q for various scenarios
- Methods of loaded Q variations
- Long pulse RF operation (high E_{acc})

Task group 2:
Mechanical tuner + piezo based detuning control

1 FTE
Potential Labs.: HZB, DESY, IJCLab, ESS, Lancaster (?)

- Review state of the art concepts, check for level of robustness, piezo as sensor
- Detuning control experiments at horizontal test stands
- Evaluate feasibility of ML sub-controller for tuning control
- First proof of principle tests at horizontal test stands
- Test with beam at e.g. SEALab/bERLinPro

Task group 3:
FE Fast Reactive tuner based detuning control

1.5 FTE
Potential Labs.: HZB, DESY, IJCLab, Lancaster (?)

- Integration of a ferro-electric fast reactive tuner with a digital LLRF system, including classic mechanical tuner for microphonics or transient detuning with the FE-FRT
- Demonstration horizontal test for microphonics compensation with FE-FRT, parallel slow tuning possible?

Task group 4:
Integrate systems into a learning/digital twin environment

3 FTE
Potential Labs.: HZB, DESY, IJCLab, Lancaster (?)

- Analyze methods to be applied to LLRF control: Optimization algorithms, training neural networks, digital twins or classic state control / model based approach, beam based feedback Supervisory control
- Fault/quench detection
- Simulate AI/ML based method on RF cavity + controller, applying virtual cavity
- Horizontal test with a real cavity setup
- Integration into a test machine with beam and different test tasks

The sum:

Partners: DESY, HZB, IJCLab, ESS, Lancaster….. more?

After discussion with experts, mainly personnel required:
Funding: 8 FTE postdoc level, 50% co-financed by labs → 4 FTE by program → 400 k€

Next generation LLRF system: 250 k€ (may be skipped, labs have to bring in hardware)

In best case: Over project time 1 Software Eng., 1 Firmware Developer, 1 Control theory Eng., 1 Physicist
→ This personnel listing is already quite a low assumption, requires more commitment by the partner labs

Open points:
- Is EUXFEL an ESFRI infrastructure?
- Would it help to mention an industry partnership/transfer, which will happen anyway?
- Spending for personnel requires an even more fail save milestone management
- Task group 1-3 have to happen closely at the labs with infrastructure/teststands/accelerator,
  task group 4 can eventually happen outside of those (AI/ML simulation, training)