

Systemy sterowania sygnałami mikrofalowymi o niskim poziomie mocy dla nadprzewodzących wnęk rezonansowych

Low-level Radio Frequency Control Systems for Superconducting cavities



Politechnika Łódzka



Wojciech CICHALEWSKI, Dr inż.

wcichal@dmcs.pl

Lodz University of Technology

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Lecture outline

- LLRF functions and accelerating-field regulation
- Superconducting cavities
- Feedback-loop structure and design
- Facility implementations and hardware platforms

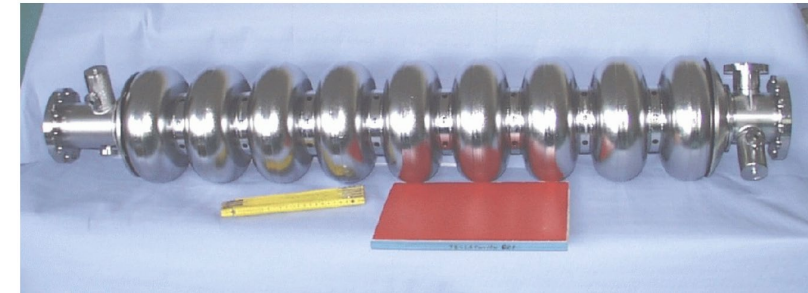
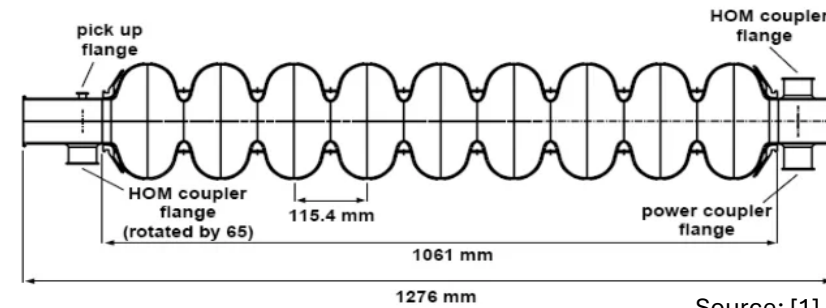
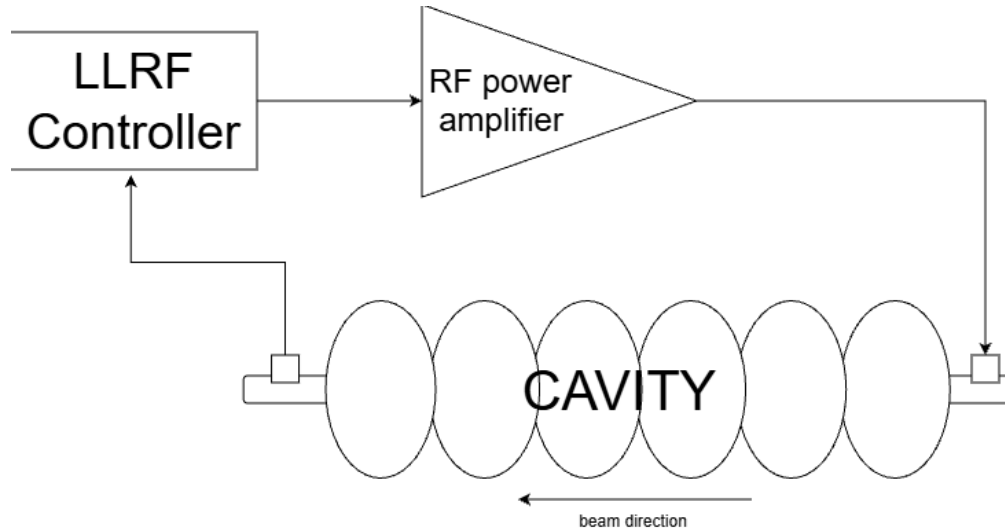


LLRF functions and accelerating field

Define the field quantity, measurement path and control objective.



What an Low Level Radio Frequency (LLRF) system controls



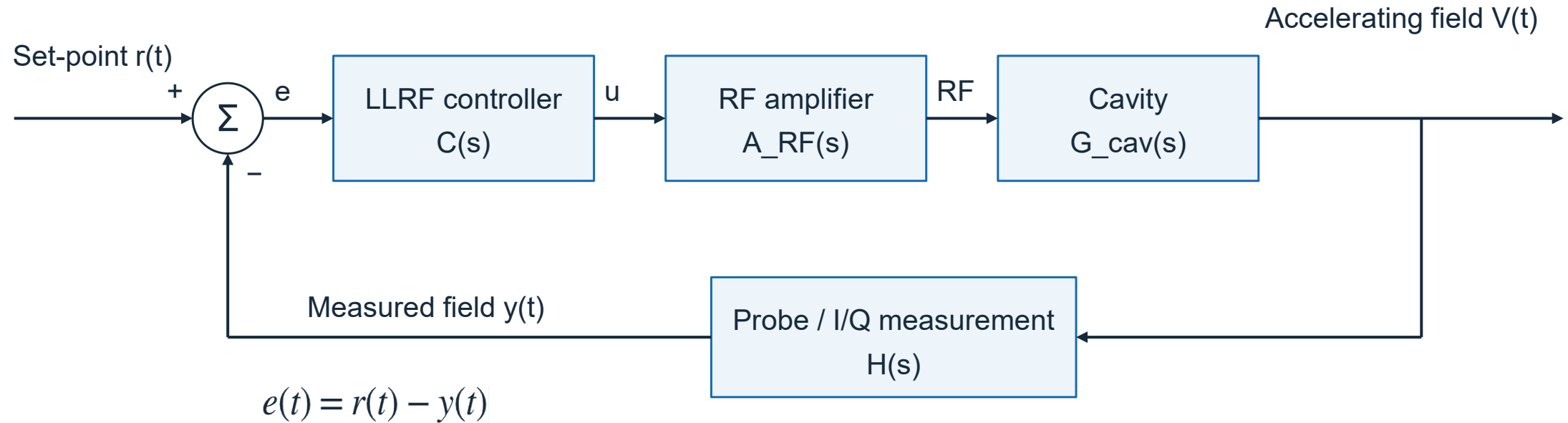
- Measure and regulate the complex accelerating field: amplitude and phase (or In-phase & Quadrature).
- Synchronize RF with the reference, timing system and beam.
- Compensate beam loading, detuning and RF-source disturbances.
- Coordinate resonance tuning, diagnostics and machine protection.
- Learning goal: connect cavity physics, loop design and hardware architecture.

[1] Vivoli, A et al., EFFECT OF CAVITY COUPLERS FIELD ON THE BEAM DYNAMICS OF THE LCLS-II INJECTOR *.

[2] TESLA TDR



The basic LLRF feedback loop

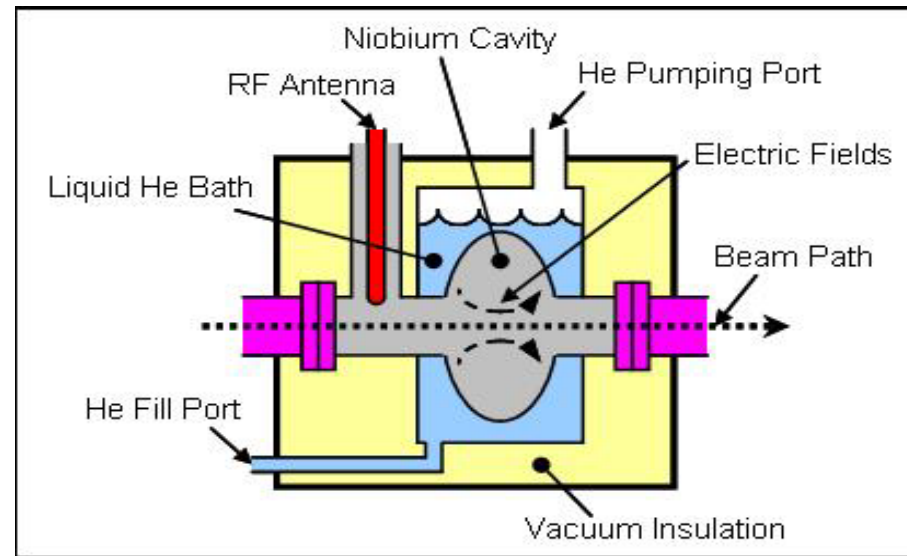


- Controller → RF power amplifier → cavity → probe/IQ measurement → negative feedback.
- Fast field loop: deterministic processing and latency.
- Slower supervisory layer: calibration, optimization, alarms and recovery.
- Field stability is meaningful only with a measurement bandwidth and time window.



Superconducting cavities

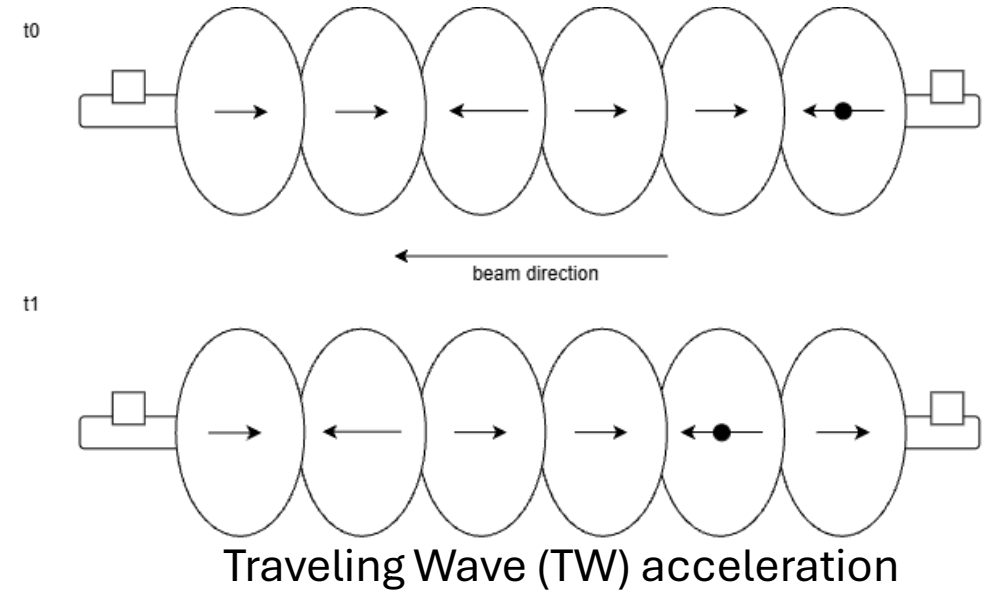
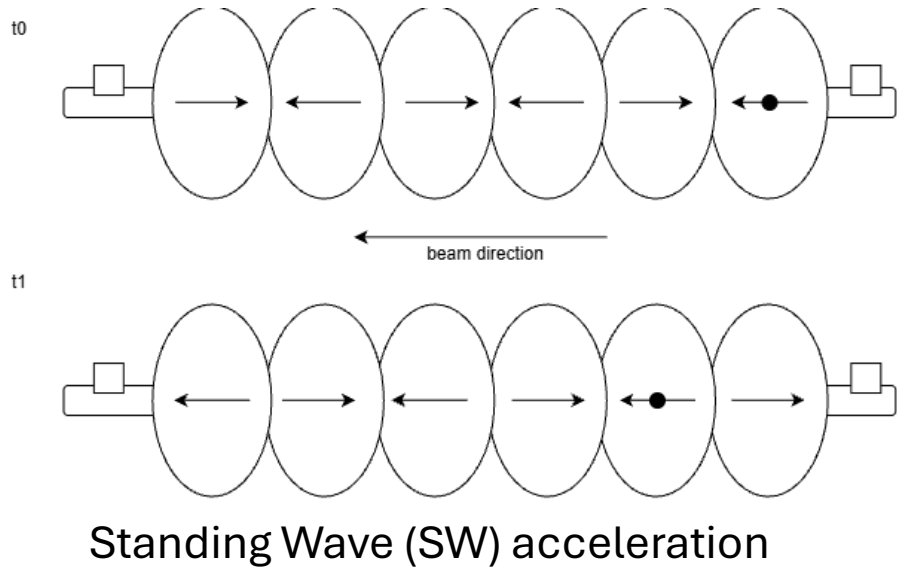
Connect RF modes, filling time, beam loading and mechanical detuning to practical SRF cavity designs.



Source: https://commons.wikimedia.org/wiki/File:SRF_Cavity_Diagram_1.jpg



The accelerating voltage



- RF electric fields transfer energy to particles at the appropriate phase.
- Effective voltage includes transit time:

Accelerating voltage $V_{\text{acc}} = \int E_z(z) e^{j\omega z/v_b} dz$

Energy gain visible by beam $\Delta E = q \text{Re}\{V_{\text{acc}} e^{j\phi_b}\}$

- Use a slowly varying complex envelope: $V(t) = I(t) + jQ(t)$.
- Amplitude $A = |V|$; phase $\phi = \text{atan2}(Q, I)$.
- The envelope approach removes the GHz carrier frequency while retaining control dynamics.



Standing-wave and travelling-wave structures

Standing wave (SW)	Travelling wave (TW)
Resonant mode stores energy	RF envelope propagates along a structure
Fixed spatial pattern; oscillating field	Phase advance per cell; net power flow
Loaded Q sets envelope decay	Group velocity sets propagation/filling time
Single-mode model often useful near resonance	Distributed or coupled-cell model required
TESLA-type SRF cavities in the case studies	Common in normal-conducting linacs

- Phase velocity provides synchronism; group velocity transports energy.
- SW/TW, normal/superconducting and pulsed/CW are separate classifications.



Pulsed RF and continuous-wave RF

Pulsed operation	CW operation
Fill → beam flat-top → decay	Persistent equilibrium with disturbances
Repeated Lorentz-force transients	Microphonics and slow drift dominate tuning
Timing-aligned feedforward and learning	Continuous regulation and resonance tracking
Integrator gating and pulse-state logic	Power overhead and long-term drift management

- RF duty factor is distinct from bunch repetition rate.
- High-gradient SW pulsed operation can need fast piezo compensation.
- Narrow-band CW SRF can need substantial reactive RF power for small detuning or fast piezo tuners feedbacks implementations .



Superconducting cavity resonator Loaded Q, bandwidth and filling

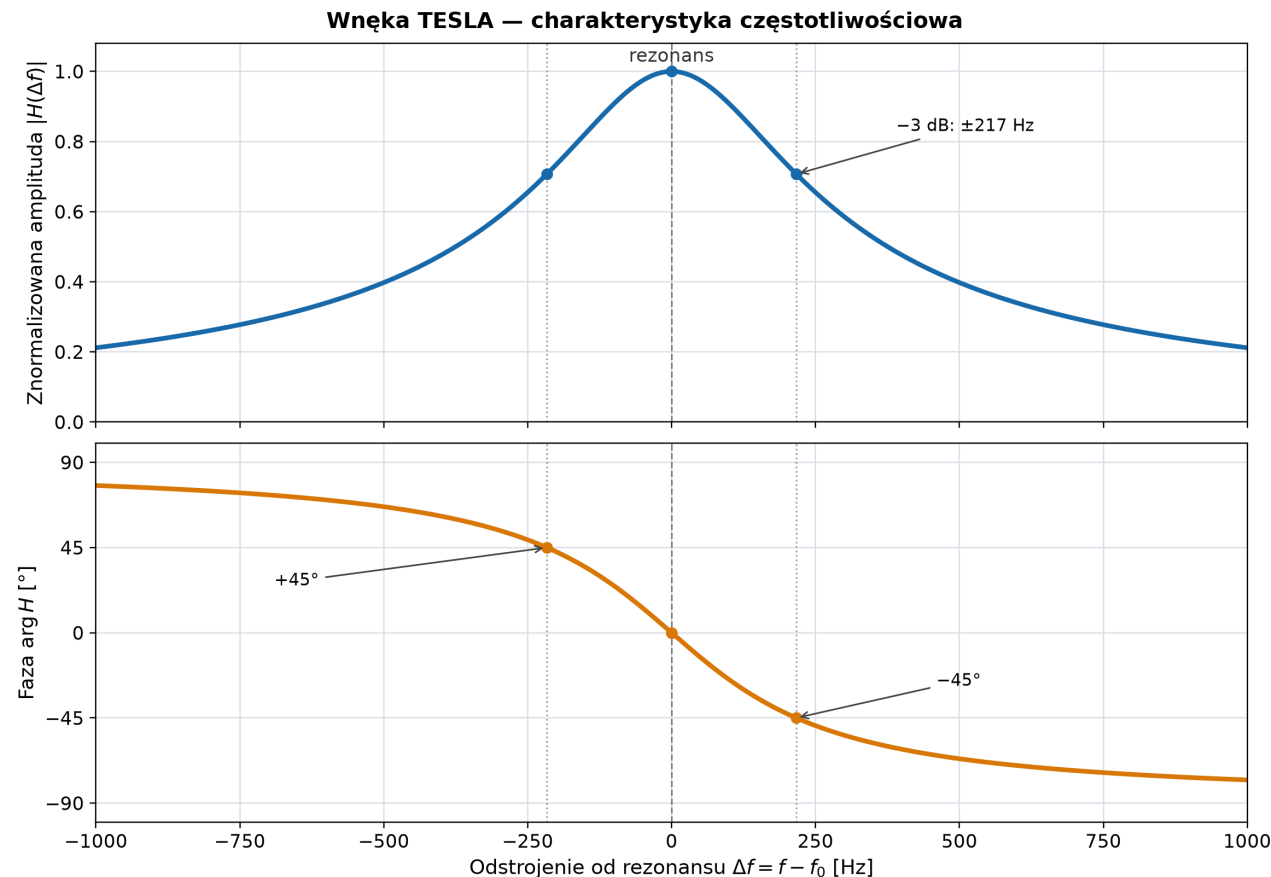
Cavity Loaded Quality factor

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{\text{ext}}}$$

$Q_L \sim Q_{\text{ext}}$ for superconducting since $Q_0 \sim 10^{10}$

Cavity Half Bandwidth

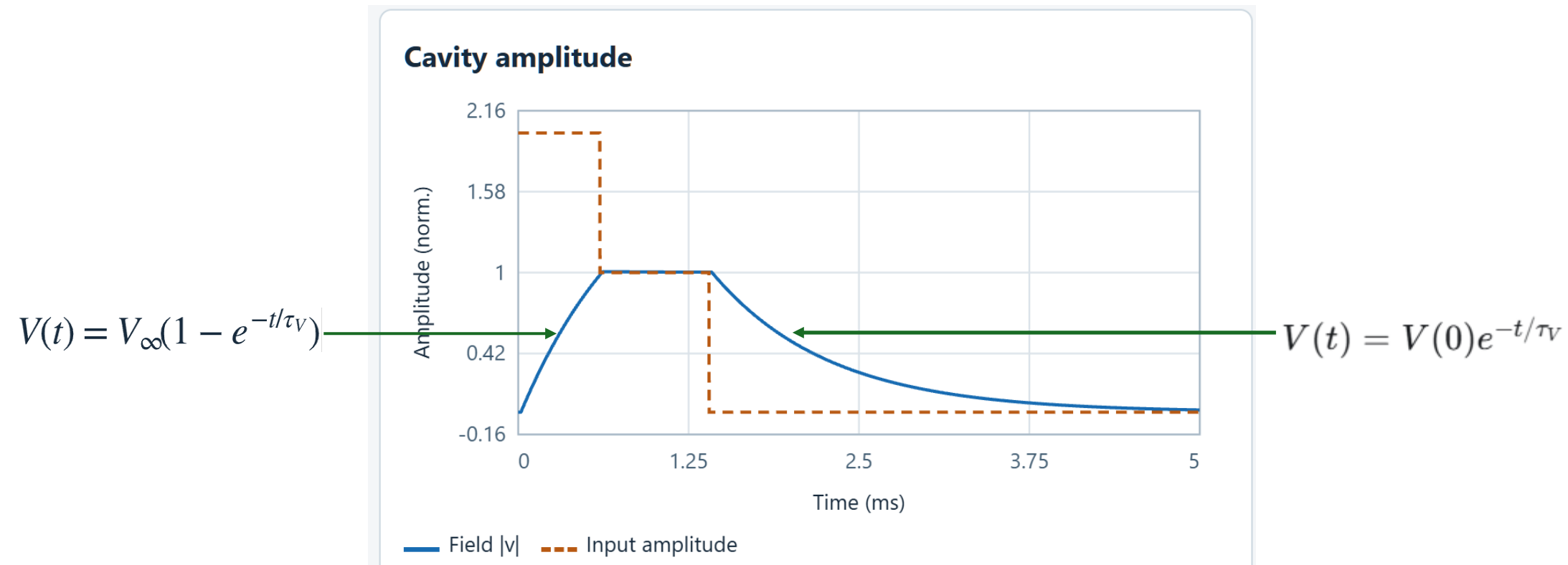
$$f_{\text{half}} = \frac{f_0}{2Q_L}, \quad a = 2\pi f_{\text{half}} = \frac{\omega_0}{2Q_L}$$





Loaded Q, bandwidth and filling

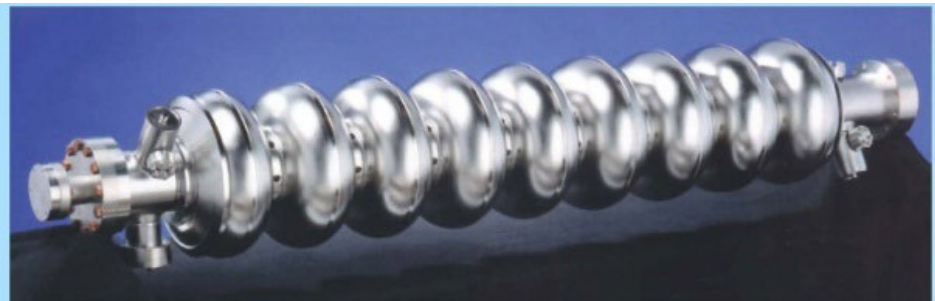
Cavity Voltage and Energy time constant $\tau_V = \frac{1}{a} = \frac{2Q_L}{\omega_0}$, $\tau_U = \frac{Q_L}{\omega_0}$



- SW filling is asymptotic; 95% field needs about $3\tau_V$ at fixed drive.
- TW filling: $t_{\text{fill}} = \int \frac{dz}{v_g(z)}$.



TESLA-type 1.3 GHz cavities



Nine-cell niobium cavity; the TESLA geometry is used at FLASH and European XFEL and is the basis of the LCLS-II 1.3 GHz linac. The π -mode field accelerates the bunch in each cell. A near-relativistic electron travels about half an RF wavelength per cell. The cavity geometry is shared, while coupling and operating points vary by facility.

The table compares facility operating values and one TESLA reference coupling point. Q_i depends on the input coupler and machine configuration; values are not maximum cavity test results.

Sources: DESY Photon Science; DESY TTF CDR; SLAC LCLS-II CDR.

Parameter	FLASH / TESLA type	LCLS-II CW
RF frequency	1.3 GHz	1.3 GHz
Accelerating cells	9	9
Active length	1.038 m	1.038 m
Operating gradient	15–24 MV/m at FLASH	16 MV/m
Intrinsic Q_0 at 2 K	$> 1 \times 10^{10}$	$> 2.7 \times 10^{10}$
Loaded Q_i	$\approx 3 \times 10^6$ reference	$< 4 \times 10^7$
Operating regime	Pulsed SRF	CW SRF



ESS elliptical cavities: medium and high beta



ESS medium-beta elliptical cavity prototype. The six-cell cavity design is selected for $\beta_{\text{geo}} = 0.67$.
ESS uses two cell geometries as proton velocity rises along the linac. The medium-beta section has six cells; the high-beta section has five. Both use 704 MHz RF and operate in superfluid helium.

Parameter	Medium beta	High beta
RF frequency	704.41 MHz	704.41 MHz
Geometric β	0.67	0.86
Accelerating cells	6	5
Operating gradient	16.7 MV/m	19.9 MV/m
Cavities in linac	36	84
Design Q_0 at 2 K	5×10^9	5×10^9
Peak RF power / cavity	up to 1.1 MW	up to 1.1 MW

ESS public design material lists 704.42 MHz in its 2016 prototype specification; the current ESS linac page lists 704.41 MHz. The slide uses the current value and rounds design parameters as published.

Sources and image: ESS Linac; Bosland et al., ESS Indico, 2016, slide 7.



Electrical model: from RLC to an envelope

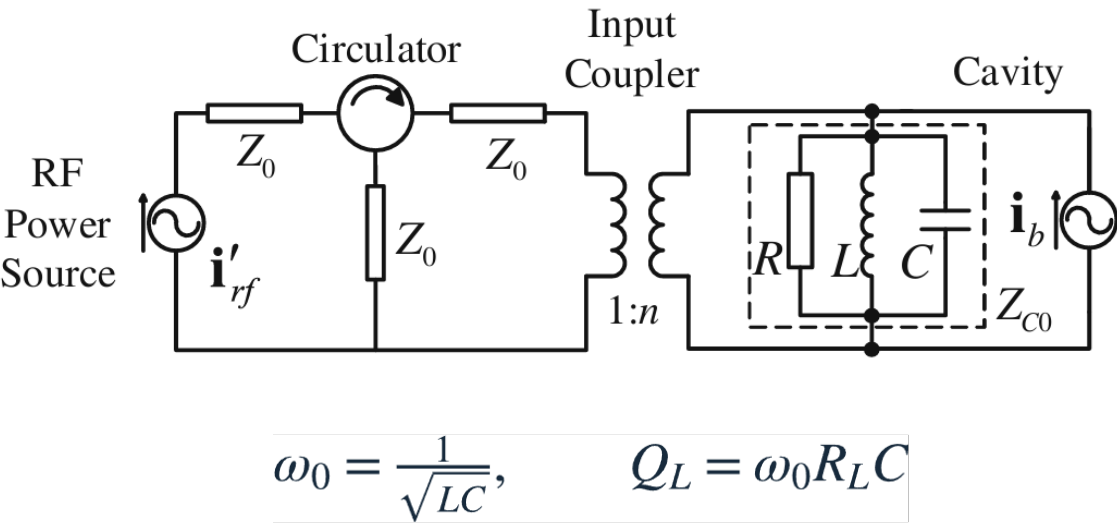


Table 3.1 Relations between the cavity parameters and the parallel RLC circuit parameters

Cavity parameter	Notation	Relation with circuit parameters
Resonance frequency	ω_0	$\omega_0 = 1/\sqrt{LC}$
Unloaded quality factor	Q_0	$Q_0 = \frac{\omega_0 W}{P_{cav}} = \omega_0 RC = \frac{R}{L\omega_0}$
External quality factor	Q_{ext}	$Q_{ext} = \frac{\omega_0 W}{P_{ext}} = \omega_0 n^2 Z_0 C$
Coupling factor	β	$\beta = \frac{P_{ext}}{P_{cav}} = \frac{Q_0}{Q_{ext}} = \frac{R}{n^2 Z_0}$
Loaded quality factor	Q_L	$Q_L = \frac{Q_0}{1+\beta}$
Normalized shunt impedance	r/Q	$R = \frac{1}{2}(r/Q)Q_0$
Loaded resistance	R_L	$R_L = R/(1+\beta) = \frac{1}{2}(r/Q)Q_L$
Half-bandwidth	$\omega_{1/2}$	$\omega_{1/2} = \frac{\omega_0}{2Q_L}$

Source: S. Simrock, Z. Geng „Low-Level Radio Frequency Control Systems”

Parallel circuit convention.

- One resonant mode → one damped complex state.
- Coupled cells → coupled RLC circuits or modal states.
- Beam is an additional current source with a signed phase.
- Port calibration maps measured waves to cavity voltage and drive.



A consistent normalized cavity model - first-order system

Cavity voltage equation $\frac{dv}{dt} = (-a + j\Delta\omega)v + a(gh - b)$

$$\frac{dh}{dt} = \omega_{\text{amp}}(u_{\text{delayed}} - h)$$

$$\Delta\omega = \omega_{\text{res}} - \omega_{\text{ref}} = 2\pi\Delta f$$

- a : cavity field decay rate (related to half bandwidth $a = 2\pi f_{\text{half}}$).
- g : identified steady-state actuator-to-field gain on resonance.
- b : normalized complex beam-loading voltage; positive real b opposes acceleration.
- h : amplifier output envelope; delay precedes amplifier dynamics.
- u : normalized control command.
- On resonance, no beam: $v_{\infty} = gu$.
- Off resonance: $v_{\infty} = \frac{agu}{a - j\Delta\omega}$.

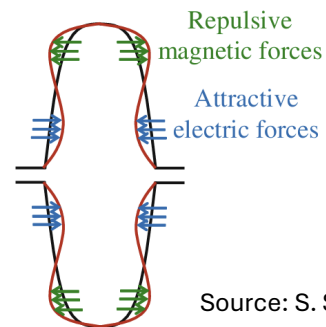


Mechanical model and electromechanical coupling

Cavity mechanical model equation $\ddot{x}_m + 2\zeta_m\Omega_m\dot{x}_m + \Omega_m^2x_m = \Omega_m^2[-K_m|v|^2 + p_m]$

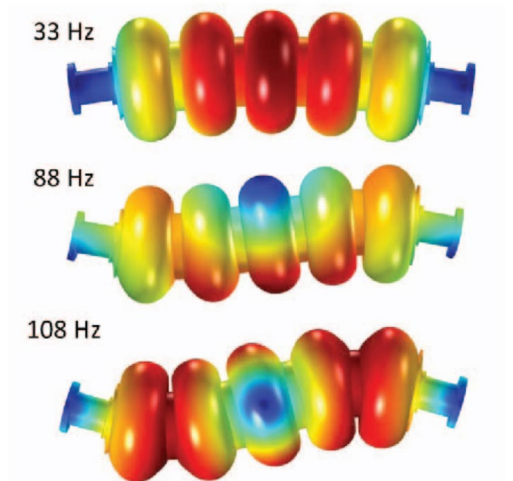
Cavity detuning equation $\Delta f = \Delta f_{\text{static}} + \sum_m x_m + \Delta f_{\text{micro}}(t)$

- x_m : modal detuning contribution in Hz; K_m : Hz per normalized $|v|^2$.
- Lorentz pressure scales with field squared and deforms the cavity.



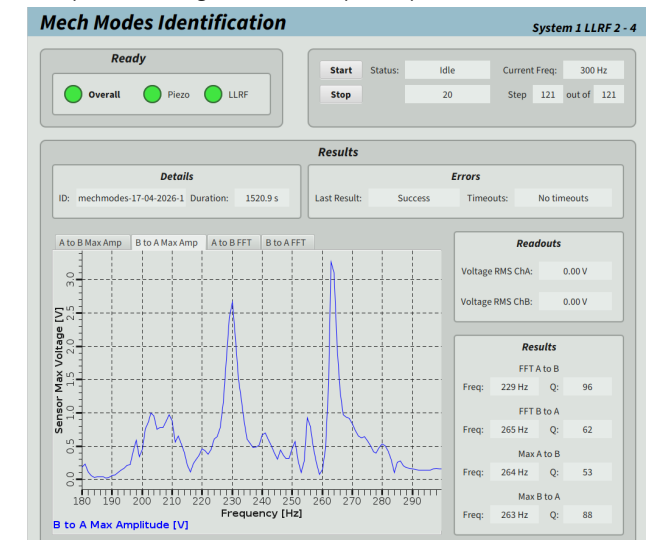
Source: S. Simrock, Z. Geng „Low-Level Radio Frequency Control Systems”

- Piezo and helium-pressure forces excite mechanical modes.
- Field $\rightarrow$ force $\rightarrow$ deformation $\rightarrow$ detuning $\rightarrow$ field: a coupled nonlinear system.
- Simulator: one mechanical mode plus prescribed sinusoidal microphonics.



Modal frequencies of the 650 MHz $\beta=0.9$ 5-cell cavi

Source: M. Awida, et al., „Multiphysics analysis of frequency detuning in superconducting RF cavities for proton particle accelerators”





Demonstration 1: open-loop cavity response

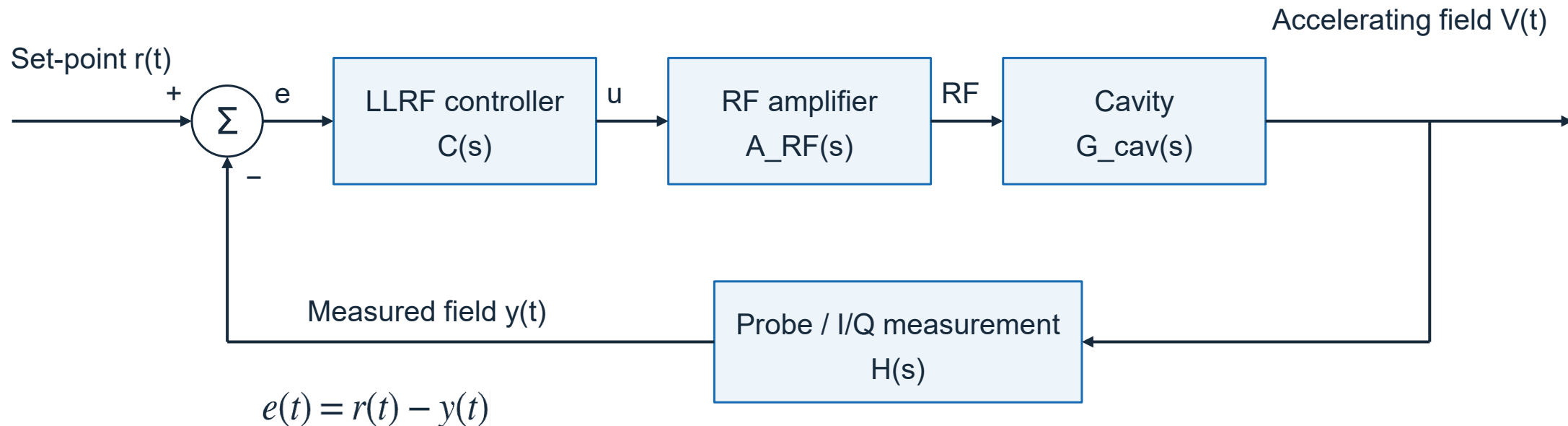
- Open simulator 1 — Cavity physics.
- SW, step, zero detuning, $K_m = 0$, $b = 0$: compare with $|1 - e^{-at}|$.
- Apply +100 Hz detuning: observe reduced amplitude and phase rotation.
- Select pulsed RF; enable Lorentz detuning and a beam step.
- Change to TW: observe entrance, exit and integrated accelerating field.
- Compare SW exponential storage with TW finite propagation filling.

Live demonstration: [open LLRF-simulators.html](https://open-llrf-simulators.html) separately.

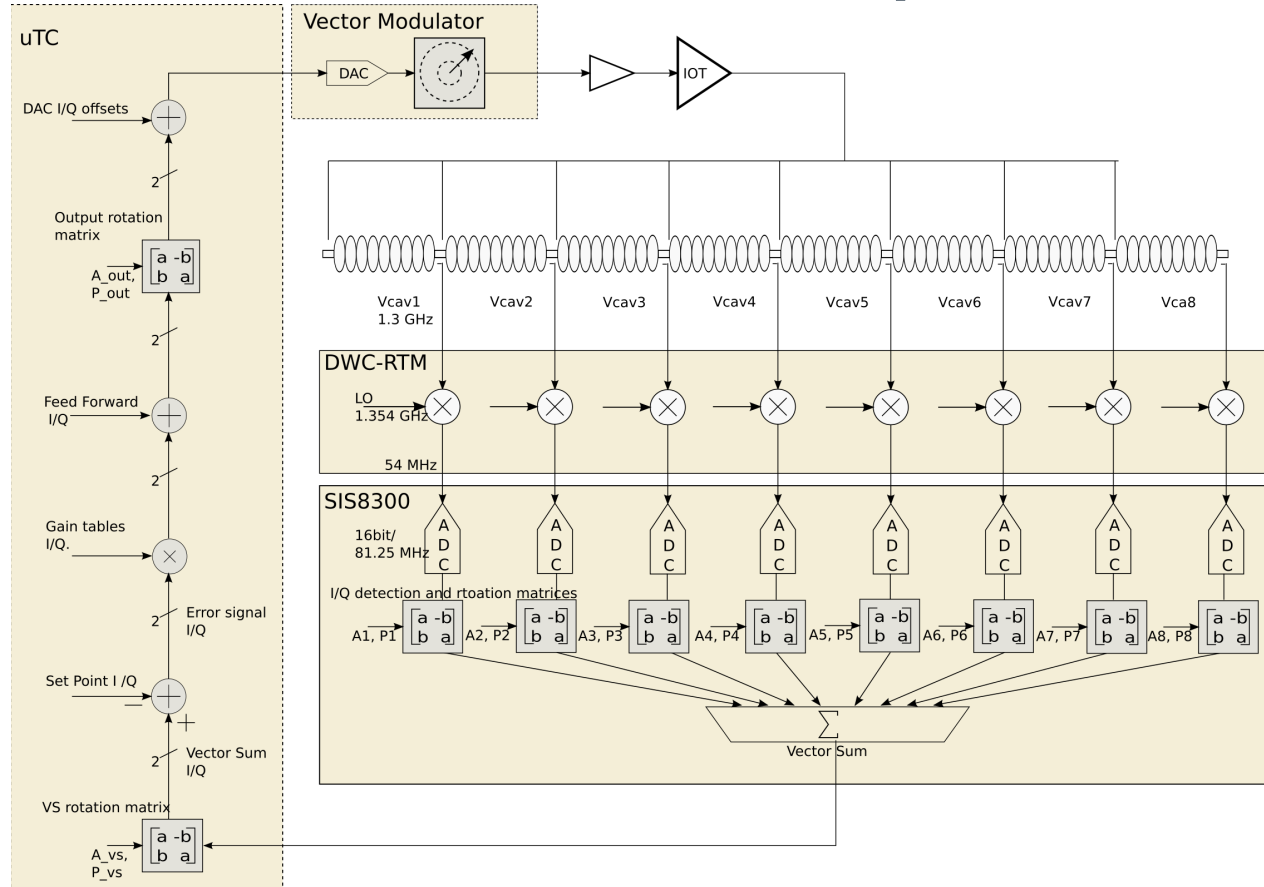


Feedback-loop structure and design

Build the digital field loop from calibrated I/Q measurement through the controller and RF actuator.



Feedback controls the complex vector



Amplitude Set-point

Error signal

$$r = A_{\text{set}} e^{j\phi_{\text{set}}}, \quad e = r - v_{\text{measured}}$$

Controller command output signal

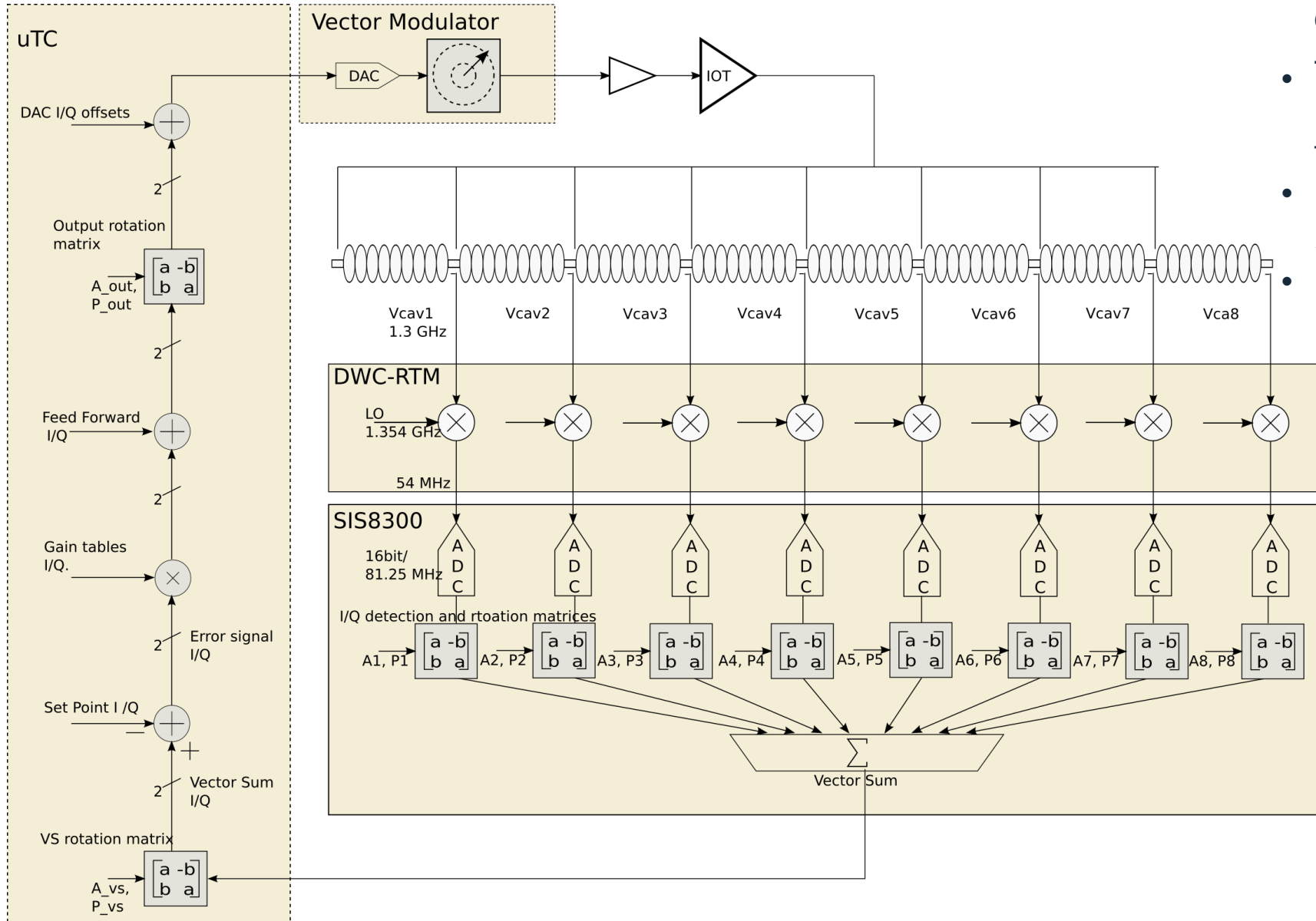
$$u_{\text{raw}} = u_{\text{FF}} + K_p e + K_i \int e \, dt - K_d \left[\frac{dv_{\text{measured}}}{dt} \right]_{\text{filtered}}$$

Controller out. limit (high power limit, input coupler limit etc.)

$$u = \text{magnitude_limit}(u_{\text{raw}})$$

- Feedforward supplies the predicted nominal command.
- Two quadratures regulate amplitude and phase near the operating point.
- Detuning couples I and Q; calibration rotates drive and measurement coordinates.
- PI is a practical starting point; D is optional and noise sensitive.

Realization of the digital field loop



- Shared clock and coherent reference; deterministic pipeline.
- Total latency includes conversion, filtering, FPGA processing, links and the actuator path.
- Choose decimation, fixed-point widths And filters together with loop bandwidth.
- Monitor probe, forward and reflected channels separately.



Configuration and operating sequence (OPTIONAL)

1. Verify signal polarity, reference phase and RF-inhibit path.
2. Calibrate probe and forward/reflected signals; determine loop rotation.
3. Identify QL, detuning, gain, amplifier bandwidth and total delay.
4. Start with low gain and adequate power headroom.
5. Enable P, then I; assess noise, disturbance rejection and saturation.
6. Gate/reset the integrator across RF states; use anti-windup.
7. Add feedforward, tuner compensation and automation after validation.



Demonstration 2: feedback responses

- Open simulator 2 — Field feedback.
- Compare Open, P, PI and filtered PID for the same beam step.
- Observe field amplitude, phase, command and saturation.
- Increase detuning or reduce command limit: regulation needs headroom.
- Increase delay and P gain: faster response can become oscillatory.
- D can add useful phase lead but amplify measurement noise.

Live demonstration: [open LLRF-simulators.html](https://open-llrf-simulators.html) separately.



Identify before tuning

Loaded Q estimation Static detuning estimation

$$\frac{d \ln |V|}{dt} = -a, \quad \frac{d \arg V}{dt} = \Delta \omega$$

$$Q_L = \frac{\omega_0}{2a}$$

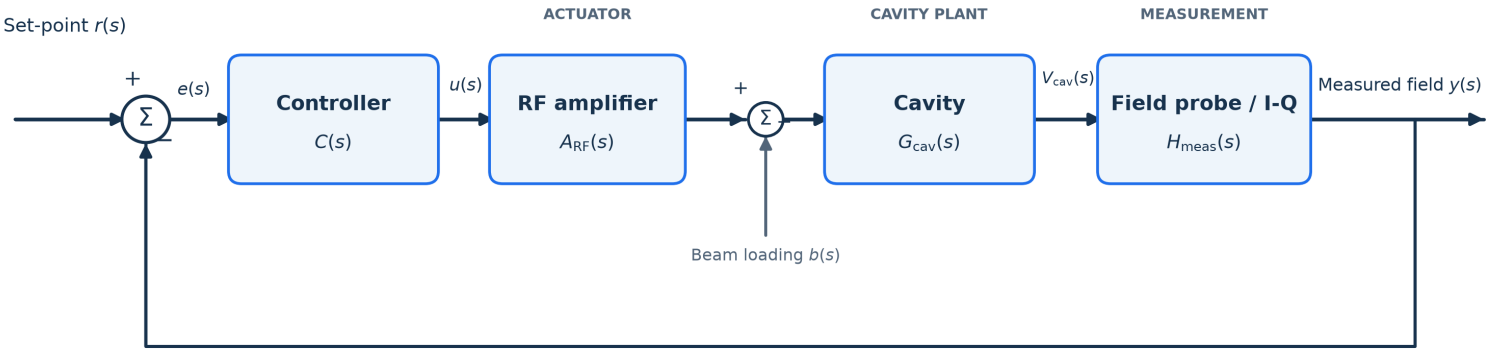
Cavity response evaluation and gain, amplifier bandwidth, delay etc detection

$$\frac{dV}{dt} = (-a + j\Delta\omega)V + a(gh - b)$$

- Decay observation gives bandwidth and detuning, over a region with adequate signal.
- Step or swept modulation identifies gain, amplifier pole and delay.
- Repeat around the actual field, tuning and beam operating point.
- Calibration errors, beam current and rapidly varying detuning can bias fits.



Plant, controller and loop transfer



Plant (actuator + cavity)

$$P_{\pm}(s) = \frac{ga}{s + a \mp j\Delta\omega} \frac{\omega_{amp}}{s + \omega_{amp}} e^{-sT}$$

$P(s) = A_{RF}(s)G_{cav}(s)$ • $L(s) = C(s)P(s)H_{meas}(s)$ • $T(s) = \frac{L(s)}{1 + L(s)}$

Negative feedback: $e(s) = r(s) - y(s)$

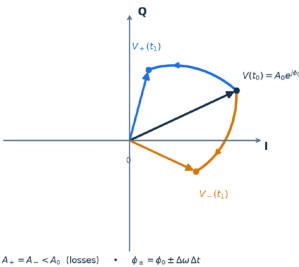
Controller

$$C(s) = K_p + \frac{K_i}{s} + \frac{K_d s}{1 + s/\omega_D}$$

$$L_{\pm} = CP_{\pm}, \quad S_{\pm} = \frac{1}{1 + L_{\pm}}, \quad T_{\pm} = \frac{L_{\pm}}{1 + L_{\pm}}$$

- The $\pm$ branches are eigenchannels of the real I/Q plant at fixed detuning.
- Resonance: the branches coincide; scalar PI tuning is then useful.
- Sensitivity S: disturbance rejection; complementary sensitivity T: tracking/noise trade-off.
- The lab evaluates the sampled, zero-order-held electrical plant and discrete controller.

I/Q field envelope: amplitude decay and phase drift



What do the + and - branches mean?

$\dot{V} = (-a + j\Delta\omega)V$
 $\Rightarrow A = -aA, \quad \phi = \Delta\omega$

Branch + $\lambda = -a + j\Delta\omega$ CCW

Branch - $\lambda = -a - j\Delta\omega$ CW

Both branches have the same amplitude decay ($-a$), while opposite signs mean opposite phase rotation.

They are a conjugate mathematical pair in the I/Q model: one cavity, not two physical modes or independent fields.



Selecting P, I and D

- Start with PI on resonance: place its zero near the cavity pole.

$$\frac{K_i}{K_p} \approx a$$

$$K_p \approx \frac{\omega_c}{ga} \sqrt{1 + \left(\frac{\omega_c}{\omega_{\text{amp}}}\right)^2}$$

- Reduce ω_c when delay or amplifier phase erodes margin.
- D: finite pole ωD , in seconds for K_d ; keep K_i in s^{-1} .
- Use both detuned branches, all unity crossings and noise/headroom checks.
- Suggested targets: roughly 45–60° phase margin; validate against uncertainty.

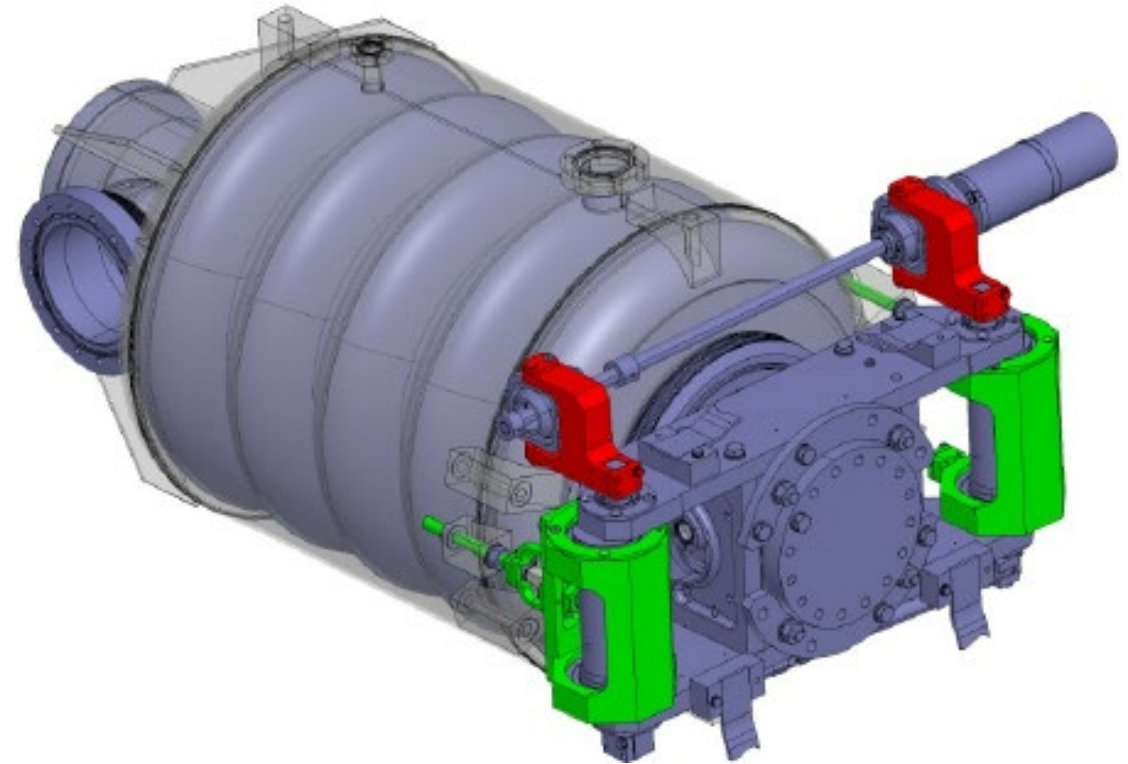
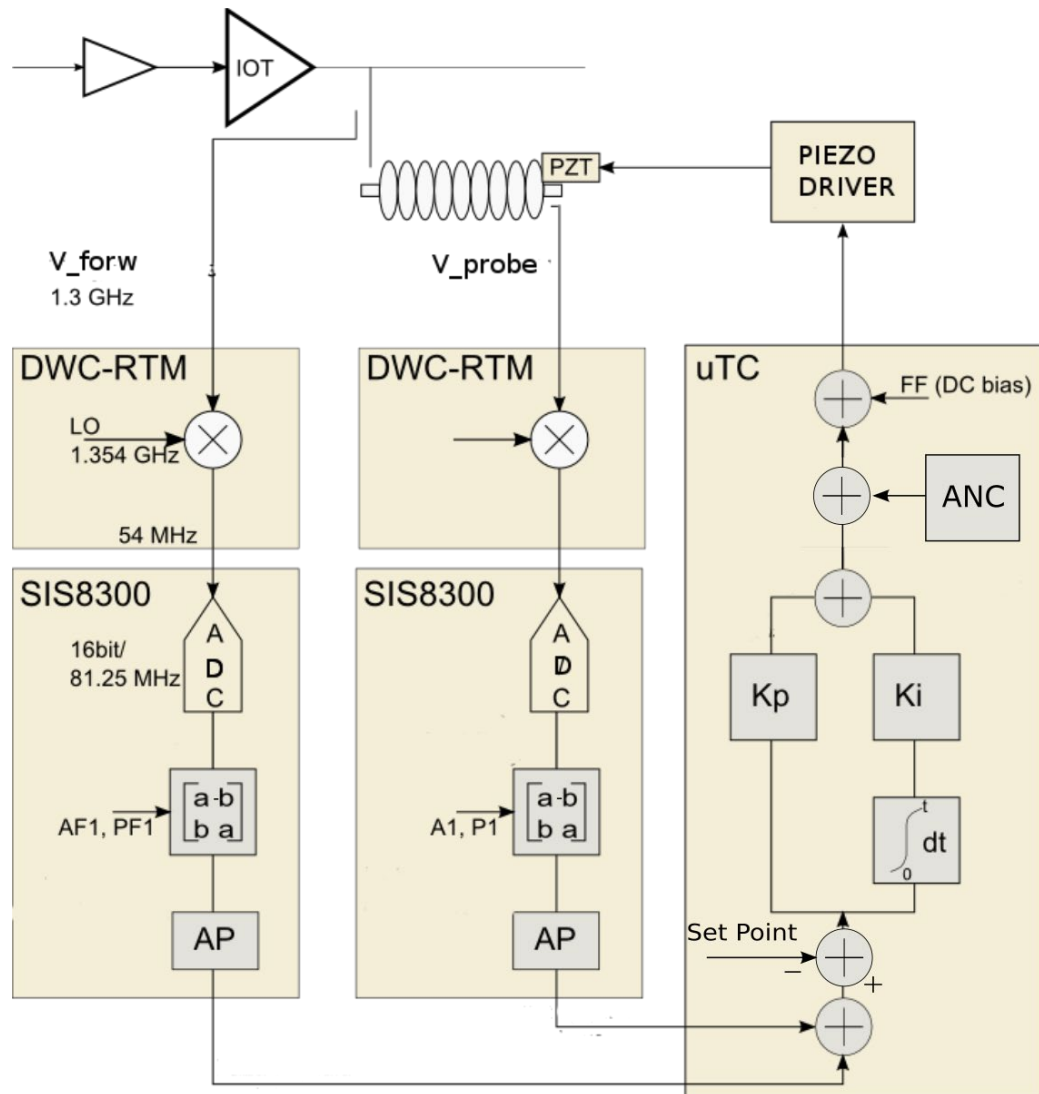


Demonstration 3: Bode-based tuning

- Open simulator 3 — PID / Bode laboratory.
- Enter f_0 , Q_L , g , amplifier bandwidth, sample period and delay.
- Suggest PI; inspect $|L|$, phase, $|S|$ and $|T|$ for both eigenchannels.
- Increase K_p ; move the crossover and watch phase margin.
- Increase K_i ; inspect low-frequency rejection and peaking.
- Add filtered D , then detuning; inspect both branches and the step response.

Live demonstration: [open LLRF-simulators.html](https://open-llrf-simulators.html) separately.

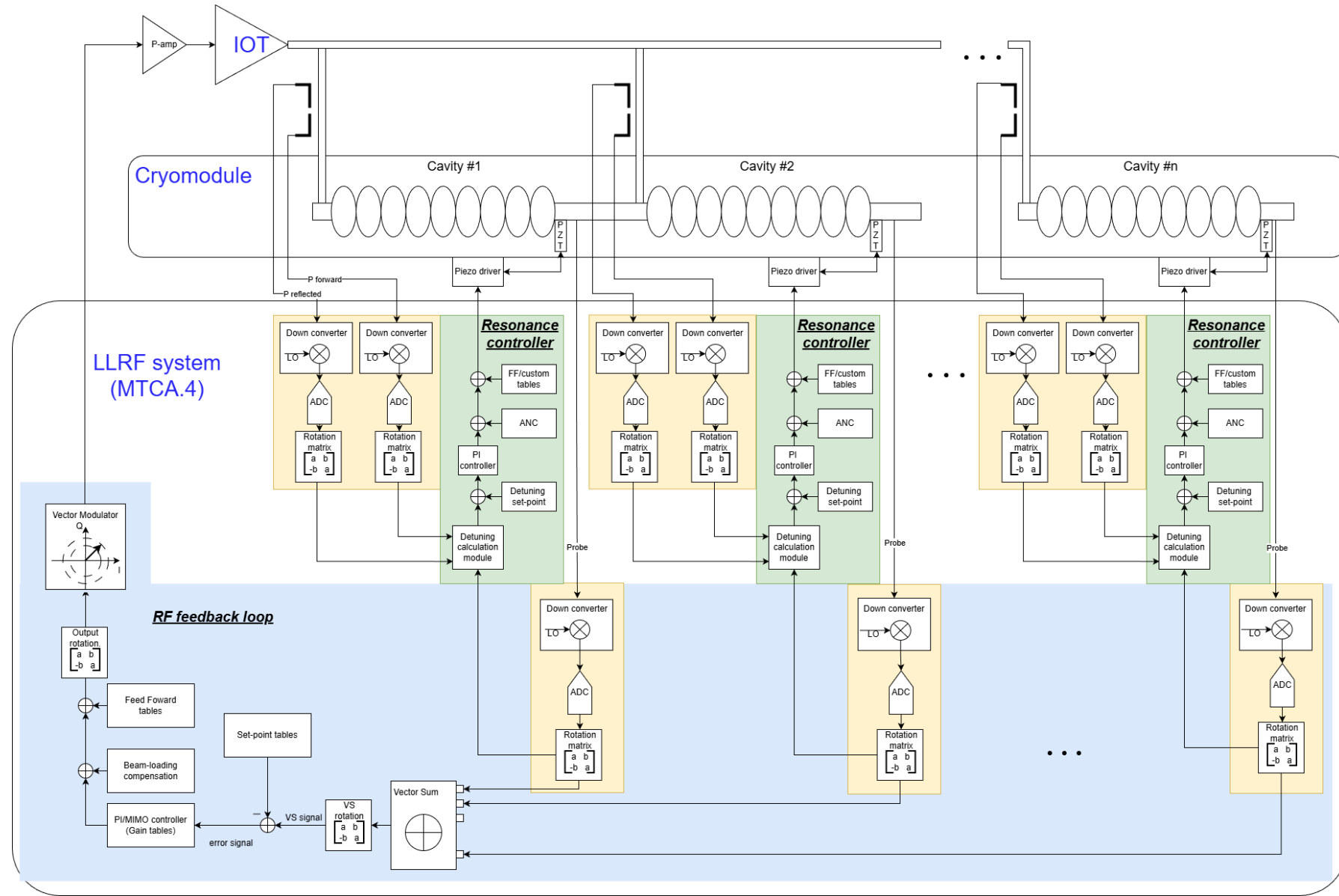
Fast Resonance controls



Source: J.P. Charrier et. al, "704 MHz HIGH POWER COUPLER AND CAVITY DEVELOPMENT FOR HIGH POWER PULSED PROTON LINACS"

- Lorentz force can detune cavity during pulse operations by hundreds of Hz (bandwidths)
- Cavity mechanical tuning done by step motors: extensive range but slow dynamics.
- Up to complex control needed including: Adaptive FF, PI, ANC,
- Essential for „next to saturation” operation and narrow band. cases

Full LLRF setup example





Facility implementations

Compare the RF control and hardware choices at FLASH, European XFEL, ESS and LCLS-II.



Four systems, two control topologies

Example	Main-linac regime	Control architecture emphasized
FLASH	Pulsed SRF, standing wave	Multiple cavities and vector-sum control
European XFEL	Pulsed SRF, standing wave	Large-scale vector-sum stations
ESS	Pulsed proton linac, NC + SRF	Individual SRF-cavity field control
LCLS-II	CW SRF, standing wave	Single source, single cavity; SEL capabilities

- Vector sum: regulate the calibrated net accelerating voltage.
- Individual control: dedicate an independent RF actuator to a cavity.
- Hardware and performance statements below refer to the cited configurations.



Platforms used by the four example systems

System	Hardware organization	Documented technology / integration
FLASH	MTCA.4 digitizers, RF RTMs, controller and CPU	FPGA field processing; shared-source control; DOOCS
European XFEL	MTCA.4; distributed measurement and central station control	SIS8300 family, DWC RTMs, uTC/TCK7 examples; optical links; DOOCS
ESS	MTCA digitizer, CPU and event receiver	SIS8300 FPGA; PCIe + trigger lines; EPICS; protection and piezo modules
LCLS-II	Dedicated receiver / RF-station / resonance chassis	ADC/DAC and FPGA carriers; optical I/Q transport; EPICS

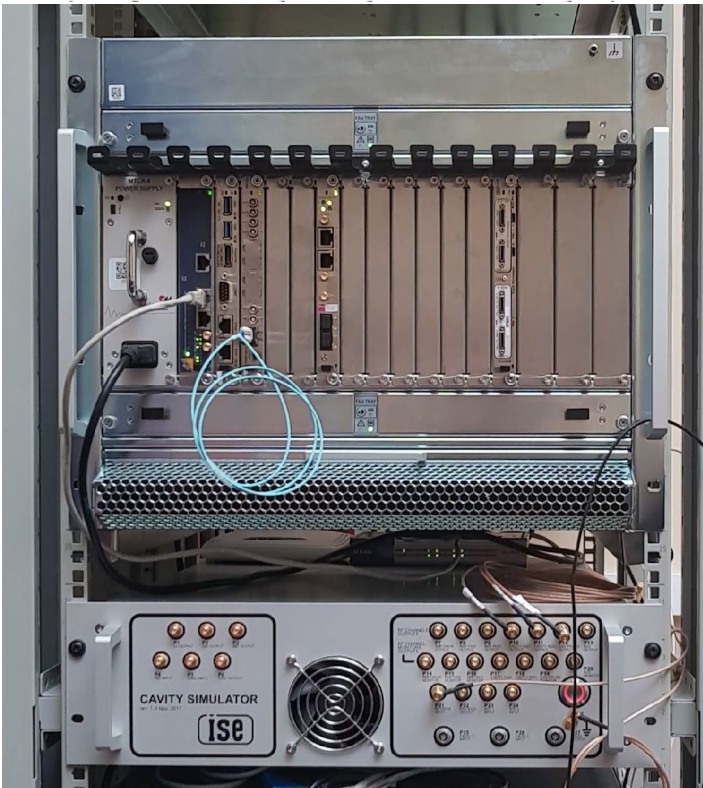
- FMC is a mezzanine interface; MTCA.4 is a crate/platform architecture.
- FPGA family, converter board and control topology are different design choices.
- Historical modules and development carriers are identified by source and date.



MicroTCA.4: the hardware platform

Component	Function in an LLRF station
AMC — Advanced Mezzanine Card	ADC/DAC, FPGA processing, timing or CPU
RTM — Rear Transition Module	RF conditioning, downconversion, modulation or tuner I/O
MCH — MicroTCA Carrier Hub	Shelf management and configured switched fabrics
Digital backplane	PCIe, Ethernet, clocks, triggers and point-to-point links
RF backplane / LO module	Precision RF/clock distribution in a compatible implementation
Power and cooling modules	Managed supplies, monitoring and heat removal

- FLASH and XFEL: MTCA.4; ESS: documented MTCA-based LLRF.
- AMC/RTM pairing separates digital processing from the analog interface.
- Platform management is separate from the real-time feedback calculation.





RF reception, conversion and coherent clocks

Probe → RF filtering / gain → mixer + LO → IF filter → ADC
→ digital downconversion → calibrated I/Q

I/Q drive → DAC → reconstruction / upconversion → amplifier

Reference → LO generation + sample clocks + phase comparison

- Heterodyne conversion moves the carrier to a manageable intermediate frequency.
- Converter bits describe quantization; noise, linearity and crosstalk determine precision.
- Clock jitter produces phase error: $|\sigma_\phi \approx 2\pi f_{\text{input}} \sigma_t|$.
- Struck example: SIS8300-L, 10 channels, 16-bit, 125 MS/s, Virtex-6.
- Direct sampling is an alternative with its own clock and alias-filter requirements.



FPGA processing and three communication paths

Path	Typical contents	Main requirement
Fast field loop	I/Q, filters, controller, limits and DAC command	Bounded latency and deterministic execution
Timing / protection	RF-start, beam markers, permits and RF inhibit	Defined event timing and failure behaviour
Supervision / DAQ	Registers, waveforms, calibration, archive and alarms	Throughput, traceability and maintainability

- FPGA: parallel logic, DSP multipliers, local memory and serial transceivers.
- PCIe connects the CPU and acquisition/control registers; Ethernet reaches services.
- Fast FPGA links can carry partial vector sums or receiver I/Q without a CPU round trip.
- CPU software implements sequencing and automation through control systems infrastructure (EPICS, DOOCS, etc)

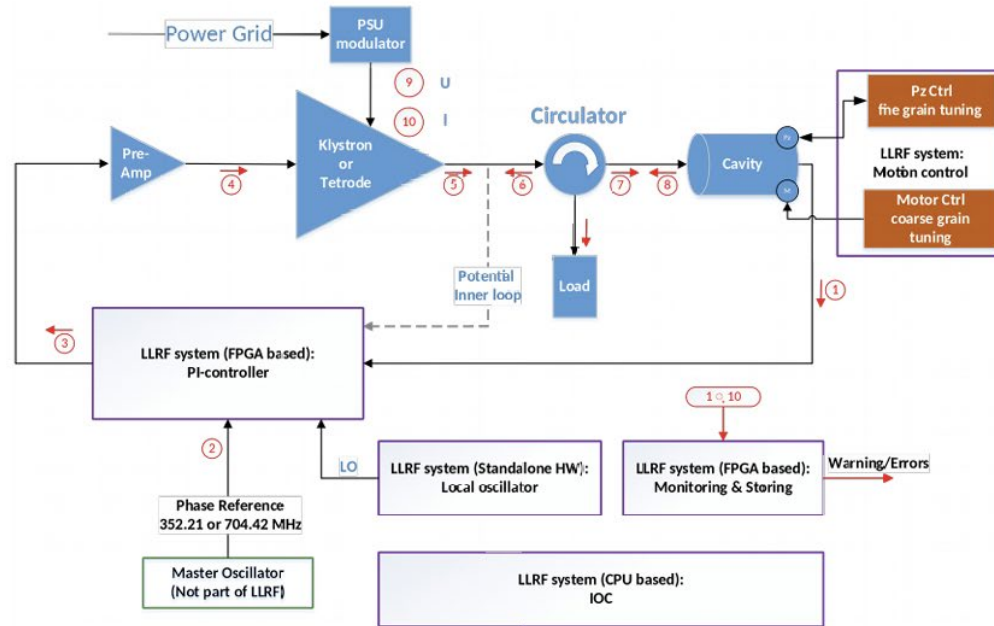


European XFEL: vector-sum control at scale

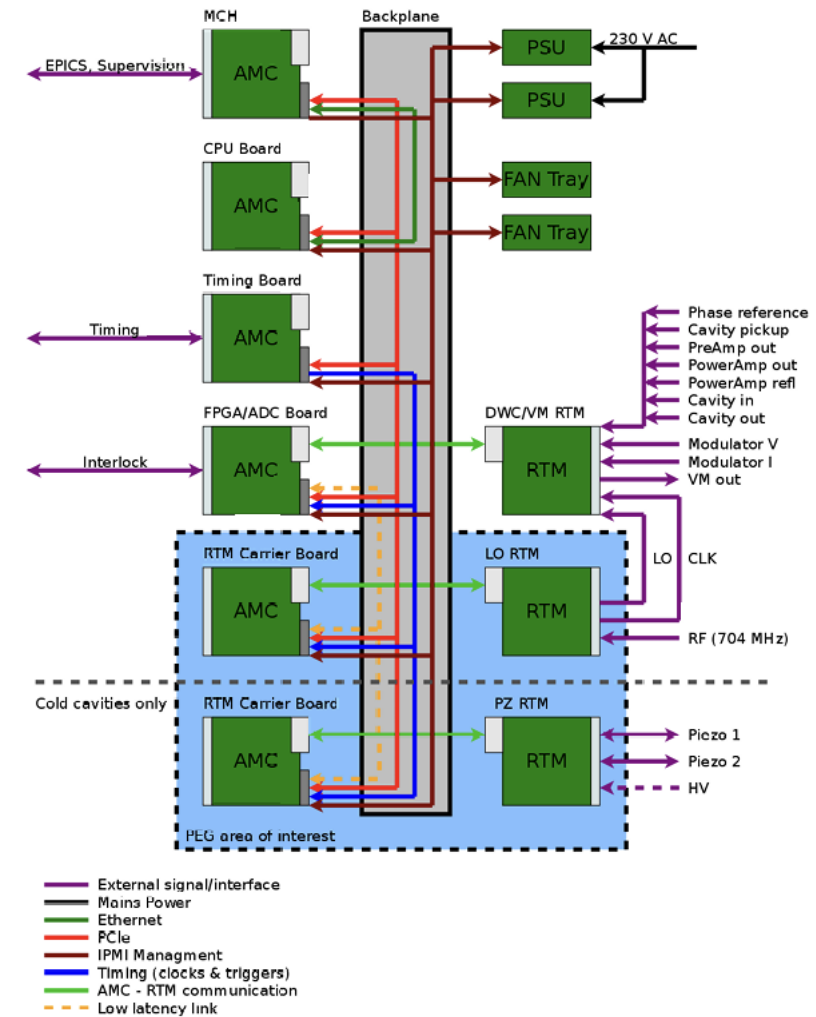
Many cavity probes → digitizer FPGA partial vector sums
→ fast links → central uTC controller → RF modulator
→ common klystron → RF distribution → cavity group
Per-cavity limits / detuning / piezo; station-level sequencing

- Calibrated sum: $V_{\Sigma} = \sum_i w_i V_i$; regulate net voltage and phase.
- 2013 modules: SIS8300L, 10 channels, Virtex-6; uTC controller family.
- Analog RTMs: downconversion and vector modulation; MTCA.4 management.
- Design target: 0.01% amplitude and 0.01° phase RMS for station field.
- Individual limits remain necessary even with a stable sum.

European Spallation Source: pulse timing and high beam loading



LLRF for ESS: Requirements and System design,
Courtesy: Anders J Johansson



- 352 and 704 MHz RF families; pulsed operation at 14 Hz.
- Design beam pulse: 2.86 ms; SRF sections use individual cavity regulation.
- 2023 report: MTCA, SIS8300 firmware, Concurrent Technologies CPU, EPICS.
- RF-system specification page gives 0.5% amplitude and 0.5° phase bounds.

LCLS-II: CW, individual sources and low-noise reception

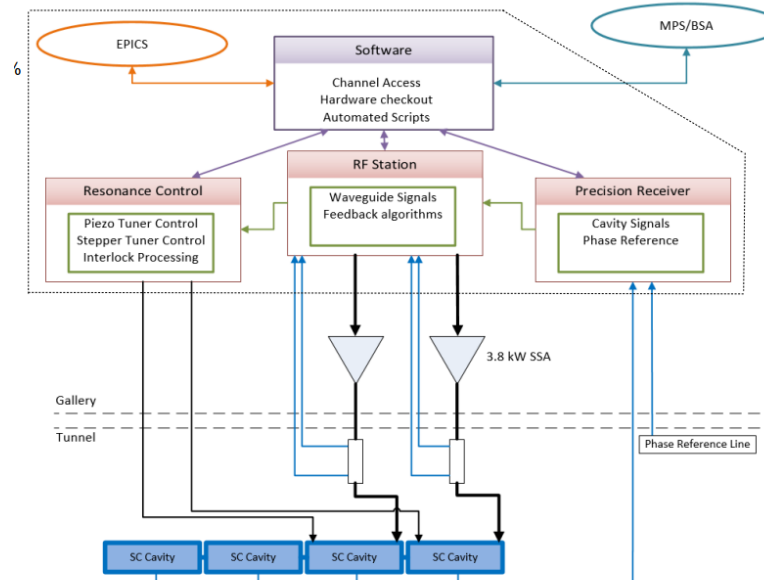
Probe + reference → Precision Receiver Chassis → optical I/Q link
→ RF Station Chassis / FPGA → upconversion → SSA → one cavity

Forward / reflected → separate monitoring path in RF station

Detuning estimator → resonance chassis → piezo + stepper

EPICS, timing, machine protection and beam feedback interfaces

- 2017 design: SSSC, 1.3 GHz CW SRF, representative $Q_L \approx 4 \times 10^7$.
- Receiver/drive separation limits RF crosstalk.
- Split IF: 20 MHz receive, 145 MHz transmit; ADC clock ≈ 94.3 MHz.
- Precision conversion, coherent clocks, thermal stability and optical transport.





Self-excited and generator-driven operation

- Generator-driven resonant operation: fixed reference frequency; detuning needs correction.
- Self-excited loop (SEL): RF oscillation follows the cavity resonance.
- Amplitude regulation and phase locking can be layered onto SEL.
- SEL supports acquisition when resonance differs from the target frequency.
- Beam operation needs the specified phase/frequency relationship to the reference.



How to compare implementations fairly

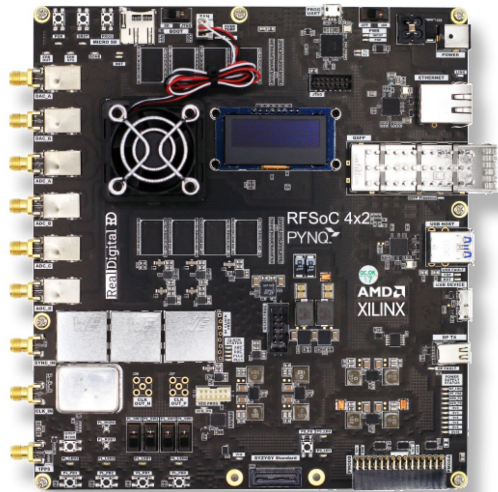
Criterion	What to examine
Actuation	One source per cavity or per group?
Measurement	Noise, drift, crosstalk and calibration accuracy
Dynamics	Loaded bandwidth, detuning, amplifier and delay
Processing	FPGA latency, links, arithmetic, mode filters
Operation	Timing, feedforward, tuner logic and recovery
Reliability	Cooling, monitoring, spares and firmware maintenance

- Specify RMS/peak, bandwidth, beam window and sum/individual field.
- A crate standard is an integration choice; it does not determine control quality.



Development directions

- Higher RF duty factor for pulsed machines: reconsider RF power, QL, tuning and heat loads together.
- Direct RF sampling / RFSoc: integrate converters and FPGA processing – phase noise considerations.
- Active work on the cavity tuning optimization - Adaptive resonance control and narrow-band microphonics reduction.
- Early systems parameters identifications (LFD coeff., piezo coefficients, mechanical modes identification etc.)
- Model-based commissioning, parameter tracking and hardware-in-the-loop testing.
- ML-assisted estimation/monitoring: validate against deterministic control baselines.



Source: www.amd.com

LLRF Topical Workshop on Advanced Feedback Control

Getting started with AI agents

Chat & code — what they are, how to drive them, and what to watch out for.

"Why, Mr. Anderson? Why do you persist... in writing it all by hand?"
— Agent Smith

Bartek Bielawski · CERN

13–15 October 2026



Summary and closing discussion

- LLRF regulates the accelerating vector while coordinating RF and resonance control.
- SW storage and TW propagation require different models.
- Electrical and mechanical dynamics couple through detuning and field squared.
- PI is a useful baseline; tuning depends on identified dynamics, delay and noise.
- Vector-sum and individual-source control reflect different actuator architectures.
- Final questions:
 - measurement, latency, detuning or power – which dominates?
 - the first experiment You would perform on an unfamiliar cavity?



Next Year

On behalf of WUT:

Low-Level RF Workshop 2027

Warsaw University of Technology, Warsaw 25.10.2027