RF Controls applications

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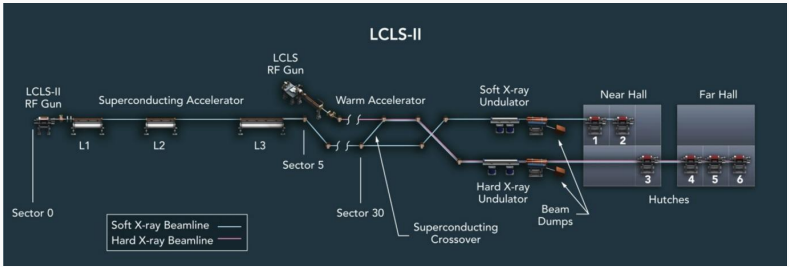
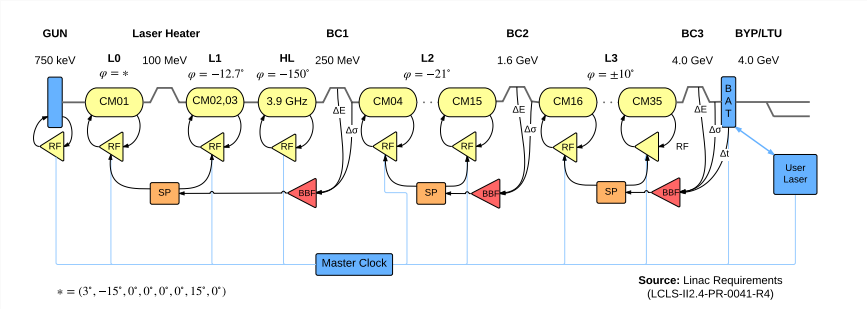
LLRF Engineering

LCLS-II LLRF system case study



LCLS-II Feedback & requirements



LLRF Requirements: 0.01% and 0.01° RMS ($\geq$ 1 Hz)

LLRF system scale

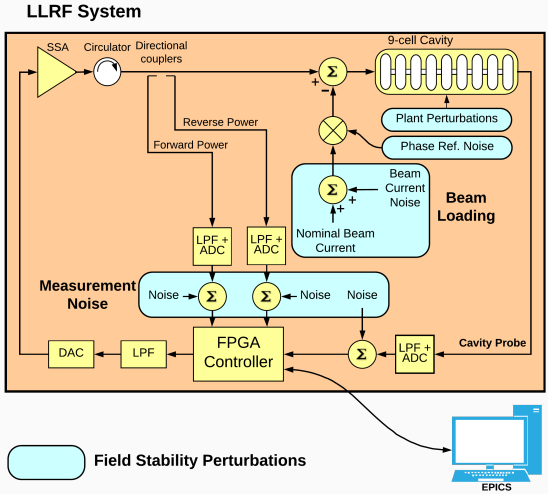
Region	Freq. (MHz)	# cavities	Type	LLRF Racks
Gun	185.7	1	NC	1
Buncher	1,300	1	NC	1
Linearizer	3,900	16	SC	4
Linac	1,300	280	SC	70

- Totals:
  - 76 LLRF racks,
  - $\sim$ 300 LLRF chassis,
  - 3 frequencies.

1.3 GHz RF System & beam parameters

Parameter	Symbol	Value	Units
RF Frequency	f_{RF}	1.3	GHz
Unloaded Q	Q_0	$2.7 \cdot 10^{10}$	unitless
Loaded Q	Q_{L}	$4 \cdot 10^{7}$	unitless
Shunt Impedance	R/Q	1036	Ω
Microphonic Detuning	Δf_{d}	± 10	Hz
Bunch Charge	Q_{b}	≤ 300	pC
Bunch Charge Error	$\Delta Q_{\mathrm{b}}/Q_{\mathrm{b}}$	± 1	%
Bunch Rep. Rate (CW)	f_{b}	≤ 1	MHz
Avg. Beam Current	I_{av}	≤ 0.3	mA

LLRF System Topology



Physics requirements to LLRF specs

Core physics requirement is 0.01% and 0.01°

Start with a coarse guideline for uncorrelated noise sources...

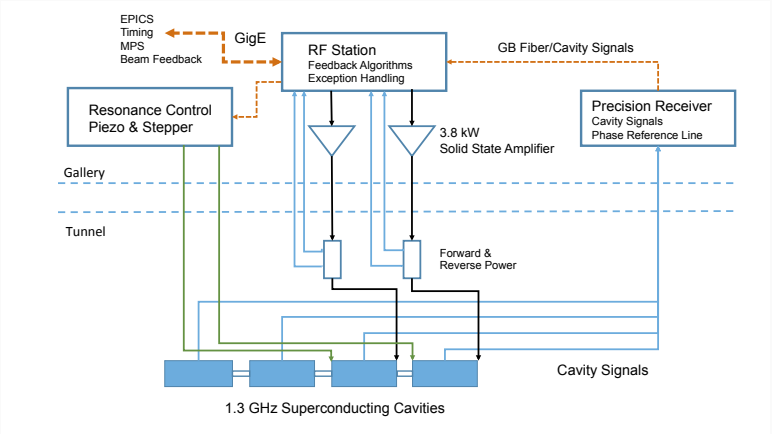
Noise Source	Amplitude	Phase
Measurement	0.005%	0.004°
PRL	N/A	0.004°
Plant pert.	0.005%	0.004°
Beam loading	0.005%	0.004°
Other/unknown	0.005%	0.004°

... and adjust with empirical evidence.

LLRF specs to engineering

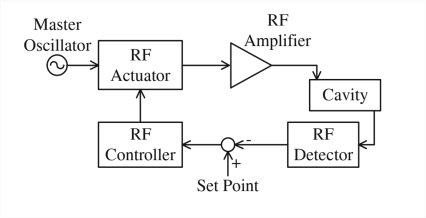
- High-Q_L superconducting $\Longrightarrow$ sensitive in the audio band and low bandwidth,
- Tight field regulation specs $\Longrightarrow$ high noise rejection,
- High noise rejection and low bandwidth $\Longrightarrow$ very high gains,
- High gains $\Longrightarrow$ measurement noise is amplified greatly,
- Tight regulation of high-Q_L SRF cavities $\Longrightarrow$ low noise design and careful engineering

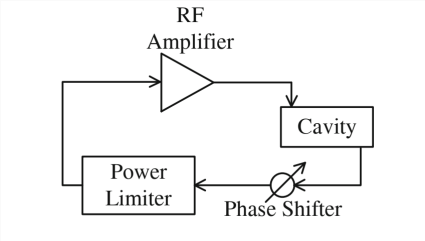
LCLS-II LLRF System Architecture



Turning on a SRF cavity

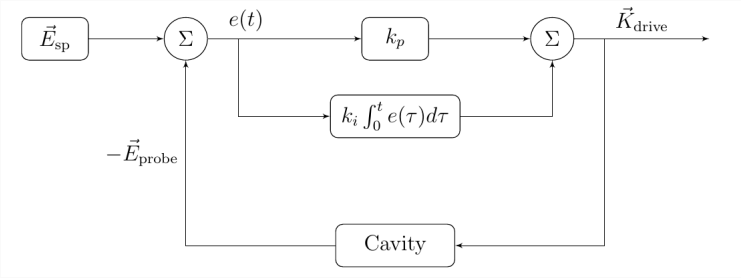
- So far we have treated the case where the amplitude and phase are locked to the frequency reference of the accelerator: Generator Driven Resonator or GDR
- When you first turn on a narrow-band cavity with an unknown resonant frequency, the RF drive at the machine reference frequency might not excite the cavity resonance
- A Self-Excited Loop (or SEL) controller, when tuned with the right phase tracks the cavity resonance





RF Controller analysis

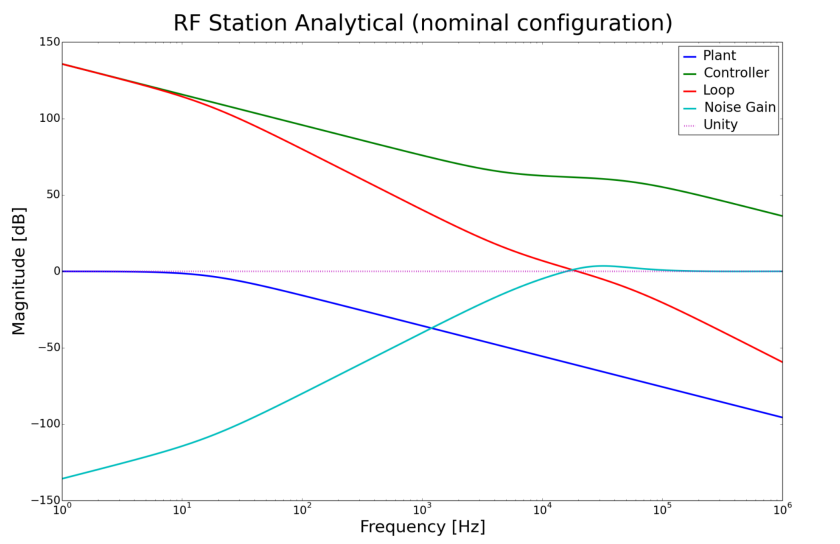
Controller


$\vec{E}_{\text{sp}}$
Σ
$e(t)$
k_p
Σ
$\vec{K}_{\text{drive}}$
$k_i \int_0^t e(\tau)d\tau$
$-\vec{E}_{\text{probe}}$
Cavity

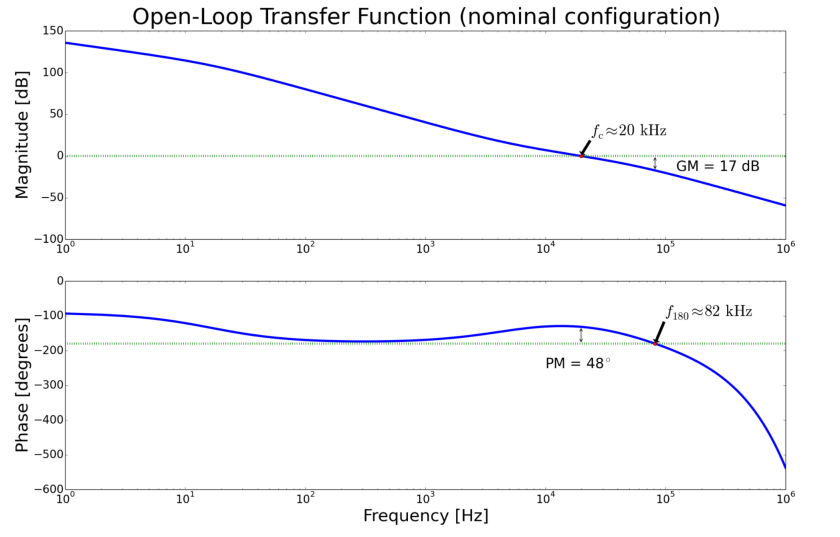
LLRF nominal configuration

Parameter	Value	Units	Implication
Intrinsic Loop Delay	1	μs	-
0-dB crossing	20	kHz	$k_p \approx 1200$
Controller Zero	5	kHz	$k_i = k_p \times 2\pi \cdot 5 \cdot 10^3$
Noise-shaping filter	53	kHz	Adds 3 μs delay

Stability analysis



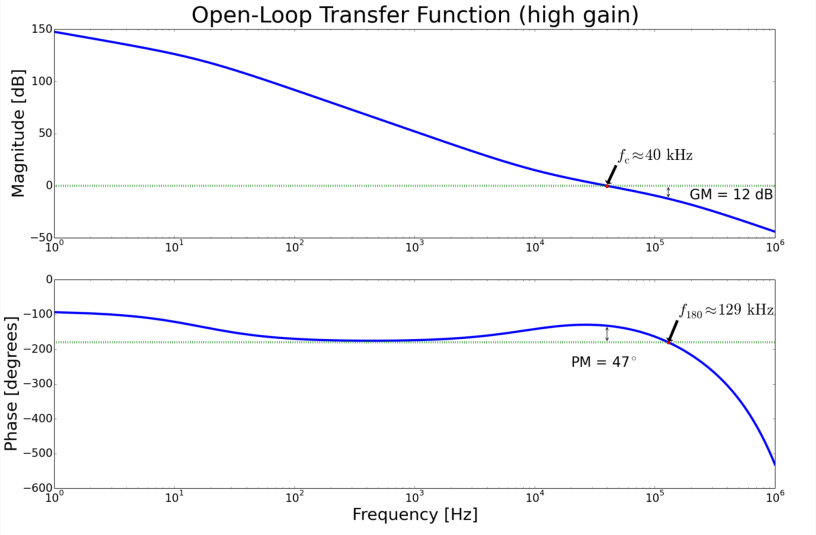
Stability analysis



LLRF high gain configuration

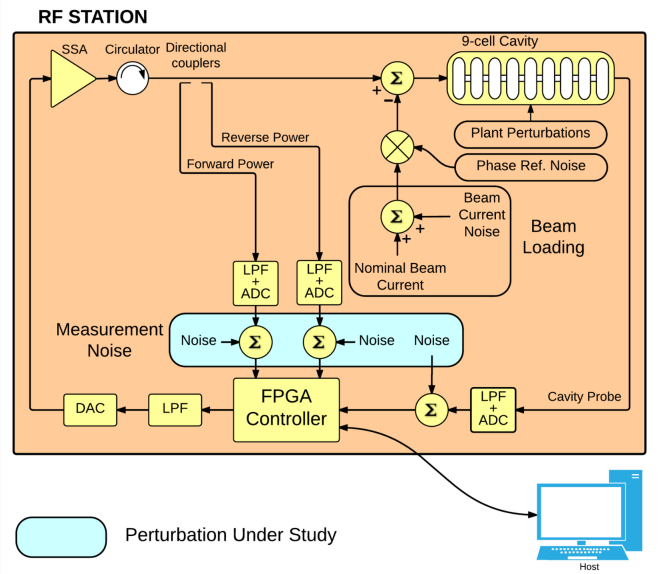
Parameter	Value	Units	Implication
Hardware Delay	1	μs	-
0-dB crossing	40	kHz	$k_p \approx 2400$
Controller Zero	10	kHz	$k_i = k_p \times 2\pi \cdot 10 \cdot 10^3$
Noise-shaping filter	160	kHz	Adds 1 μs delay

Stability analysis

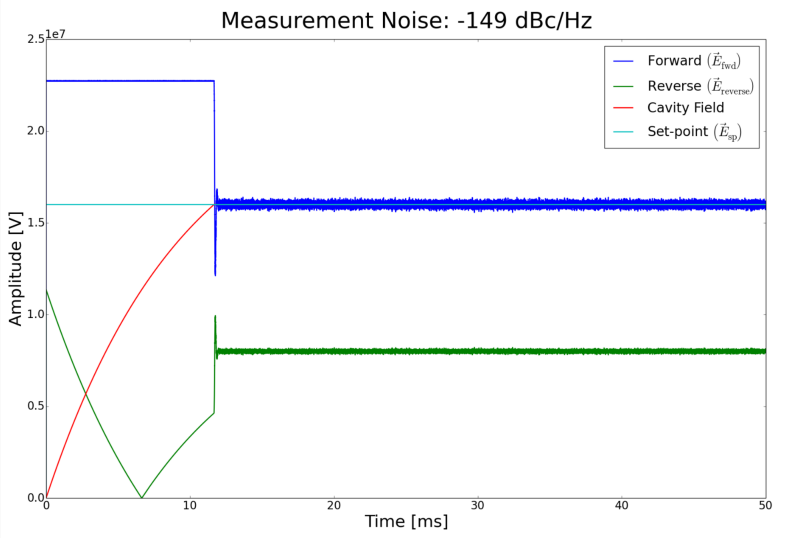


Noise analysis

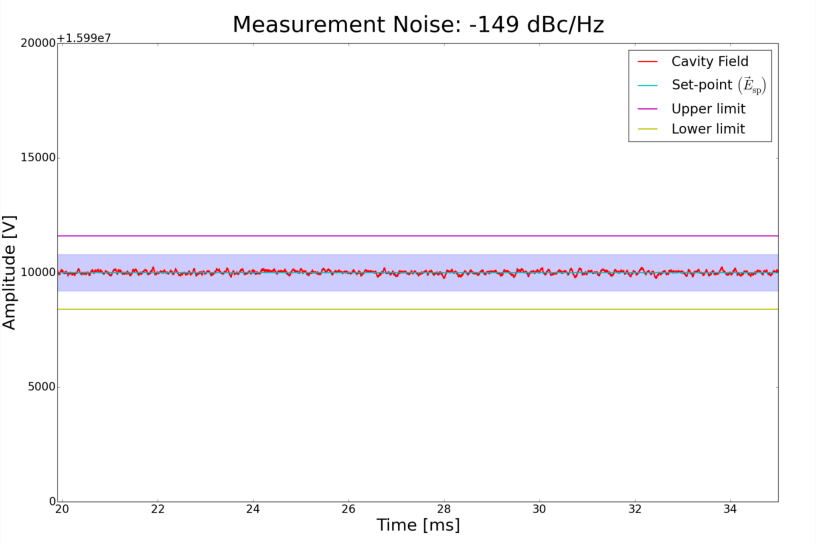
Noise analysis: Measurement noise



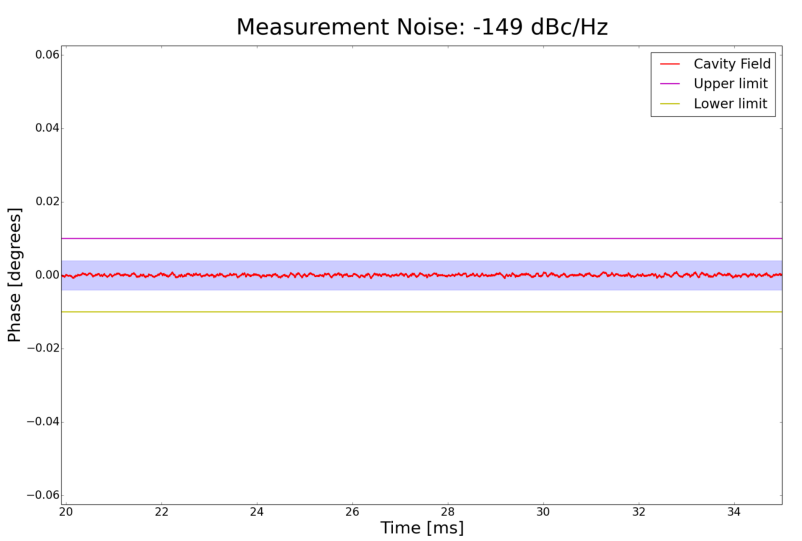
Measurement noise: Nominal configuration



Measurement noise: Nominal configuration

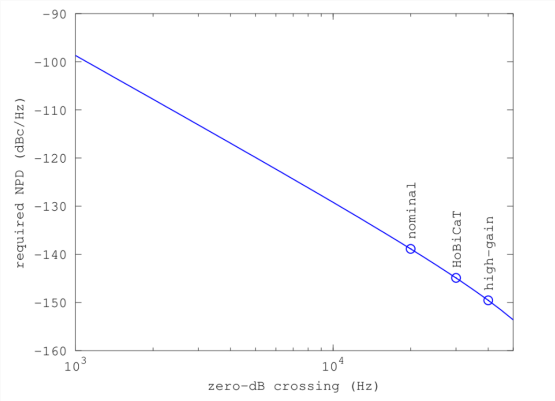


Measurement noise: Nominal configuration



Measurement noise: Impact on SSA noise

- Assuming we can tolerate around 4% RMS (amplitude) SSA drive noise, higher gains require lower levels of measurement noise

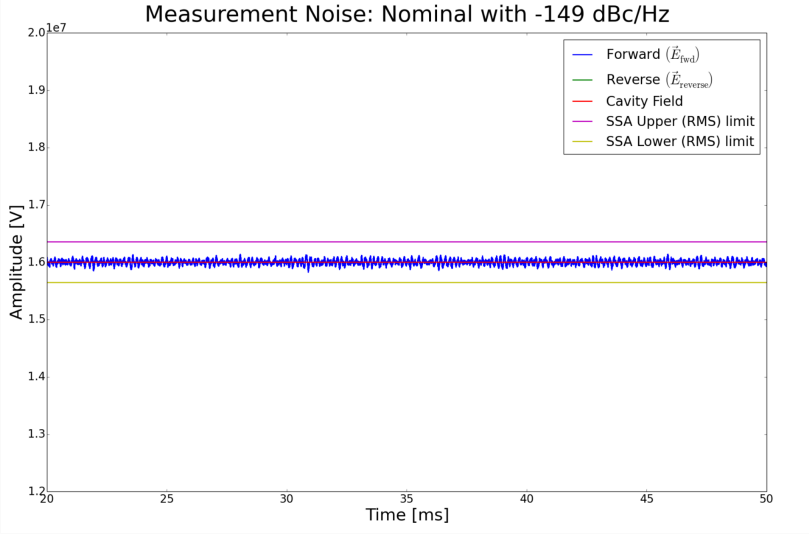


Measurement noise: Impact on SSA

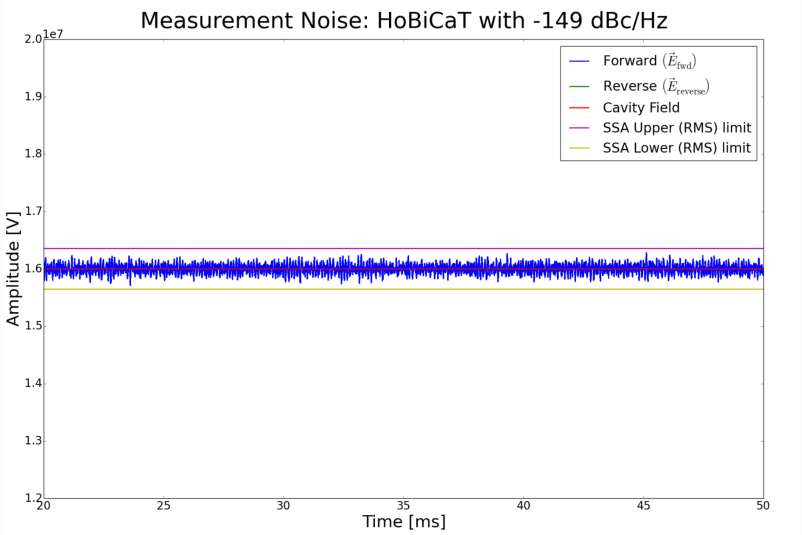
- Measurement noise goal: Establish design noise target at -149 dBc/Hz in order to support these modes of operation

Configuration	0-dB crossing	Gain	Required NPD
Nominal	20 kHz	1200	-138 dBc/Hz
HoBiCaT	30 kHz	1800	-144 dBc/Hz
High Gain	40 kHz	2400	-149 dBc/Hz

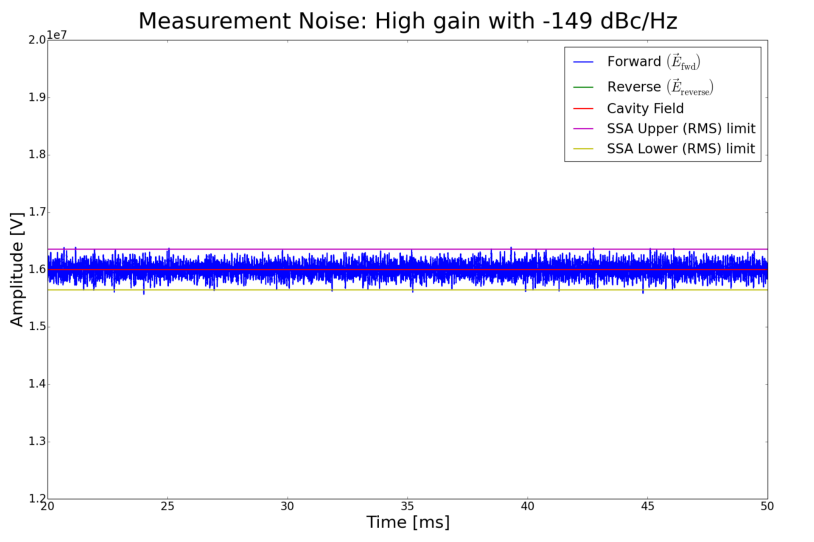
Measurement noise: Nominal configuration



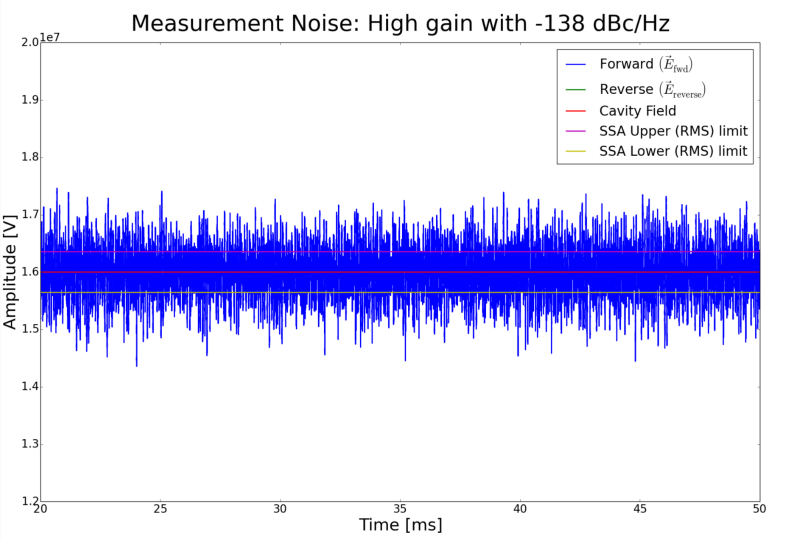
Measurement noise: HoBiCat configuration



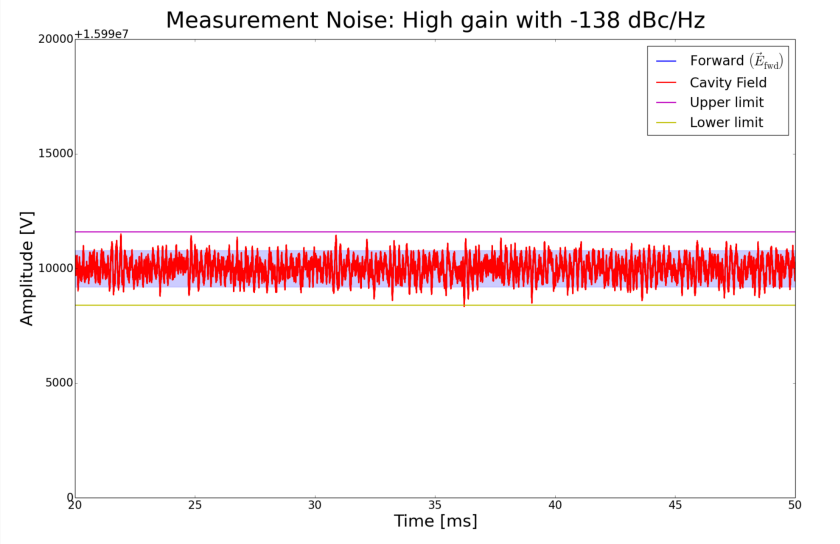
Measurement noise: High gain configuration



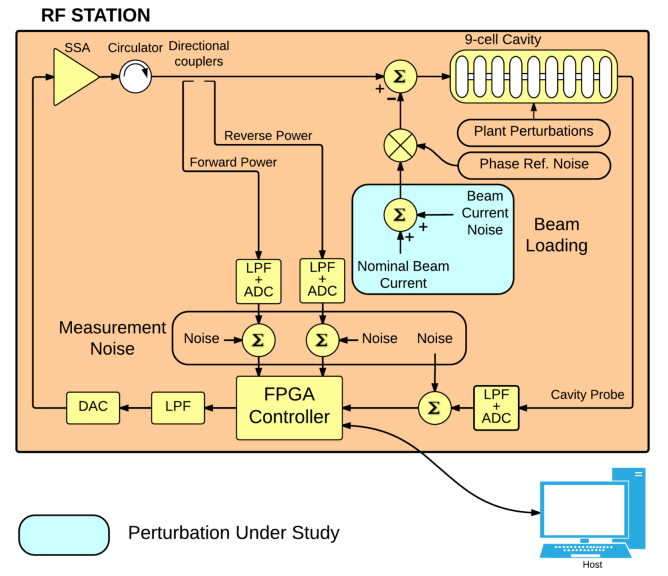
Measurement noise: High gain configuration



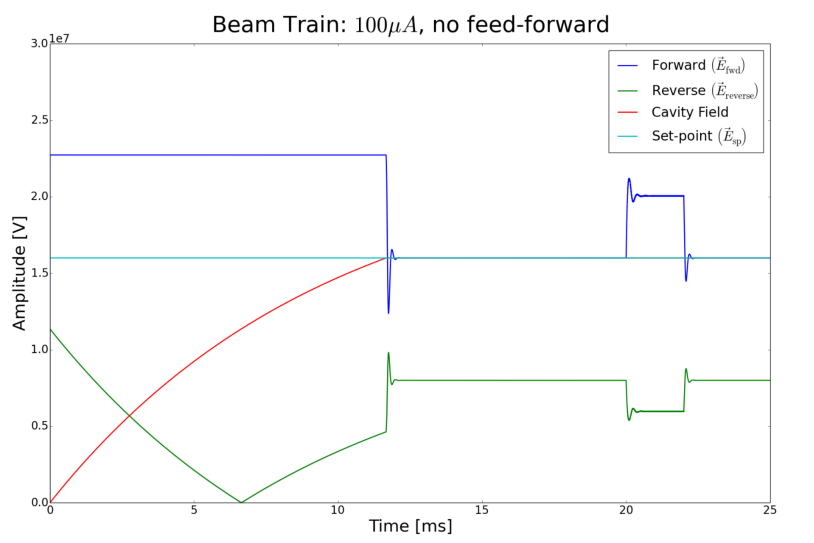
Measurement noise: High gain configuration



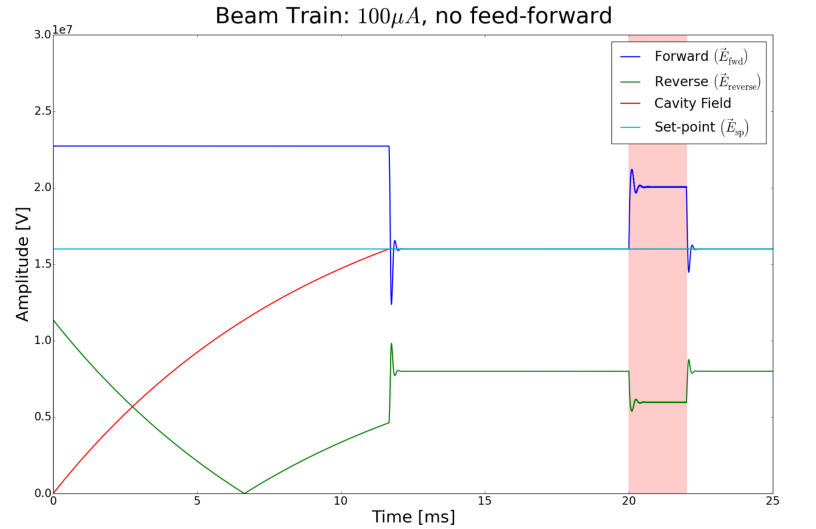
Noise analysis: Beam loading



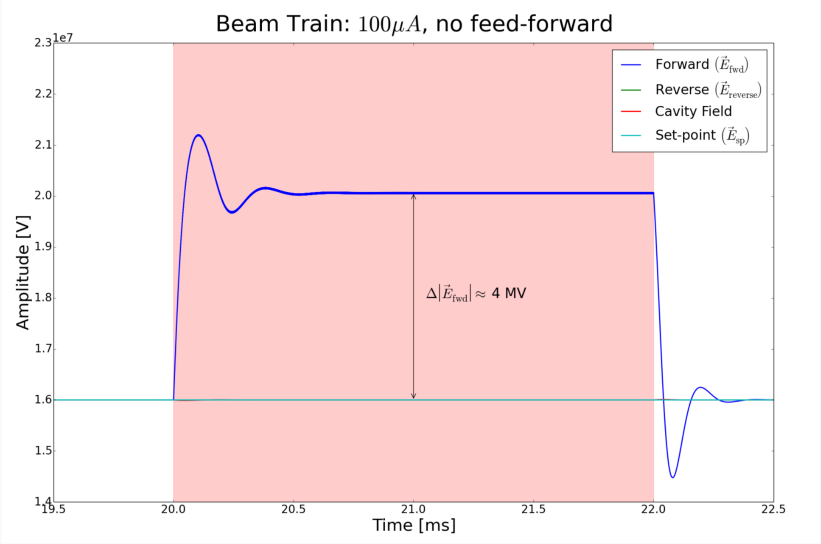
Beam loading



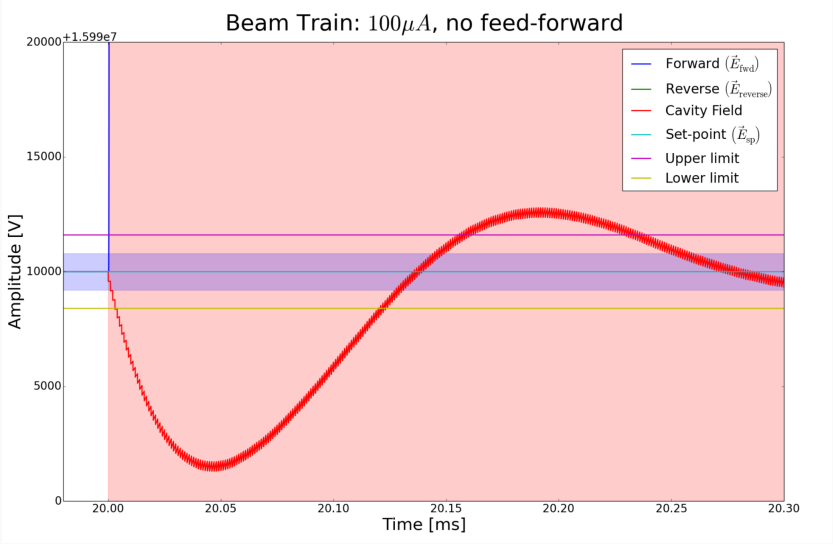
Beam loading



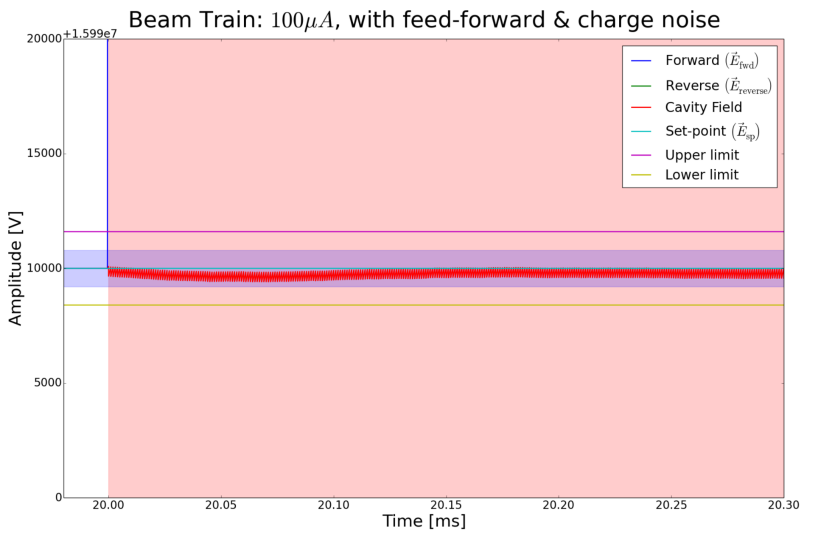
Beam loading



Beam loading

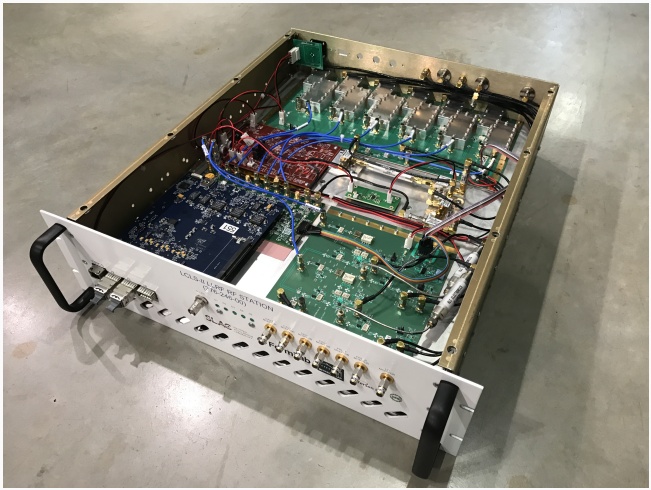


Beam loading



Implementation

LCLS-II LLRF RFS Chassis



Performance results