Longitudinal beam dynamics and feedback

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Outline

I. Performance status
- Achieved beam currents
- Beam abort rates
- Run 4 improvements

II. Low group-delay woofer

III. Modeling of LLRF and LFB

IV. Limiting factors, unresolved issues

V. Summary

Performance status

In the current RF, LFB, and woofer configurations we have achieved currents

- HER: 1590 mA
- LER: 2541 mA

Average beam abort rate due to longitudinal instabilities and LFB hardware failures

- HER: 0.39 aborts/day (0.33 September-December, 0.41 January-July)
- LER: 0.23 aborts/day (0.07 September-December, 0.30 January-July)

Abort rates increased in both HER and LER in the second part of the run due to hardware failures and higher average beam currents

Ring	Sep-Dec max	Jan-Jul max	Ratio	Sep-Dec mean	Jan-Jul mean	Ratio
HER	1319 mA	1590 mA	1.21	764 mA	1035 mA	1.35
LER	1998 mA	2541 mA	1.27	1076 mA	1734 mA	1.61

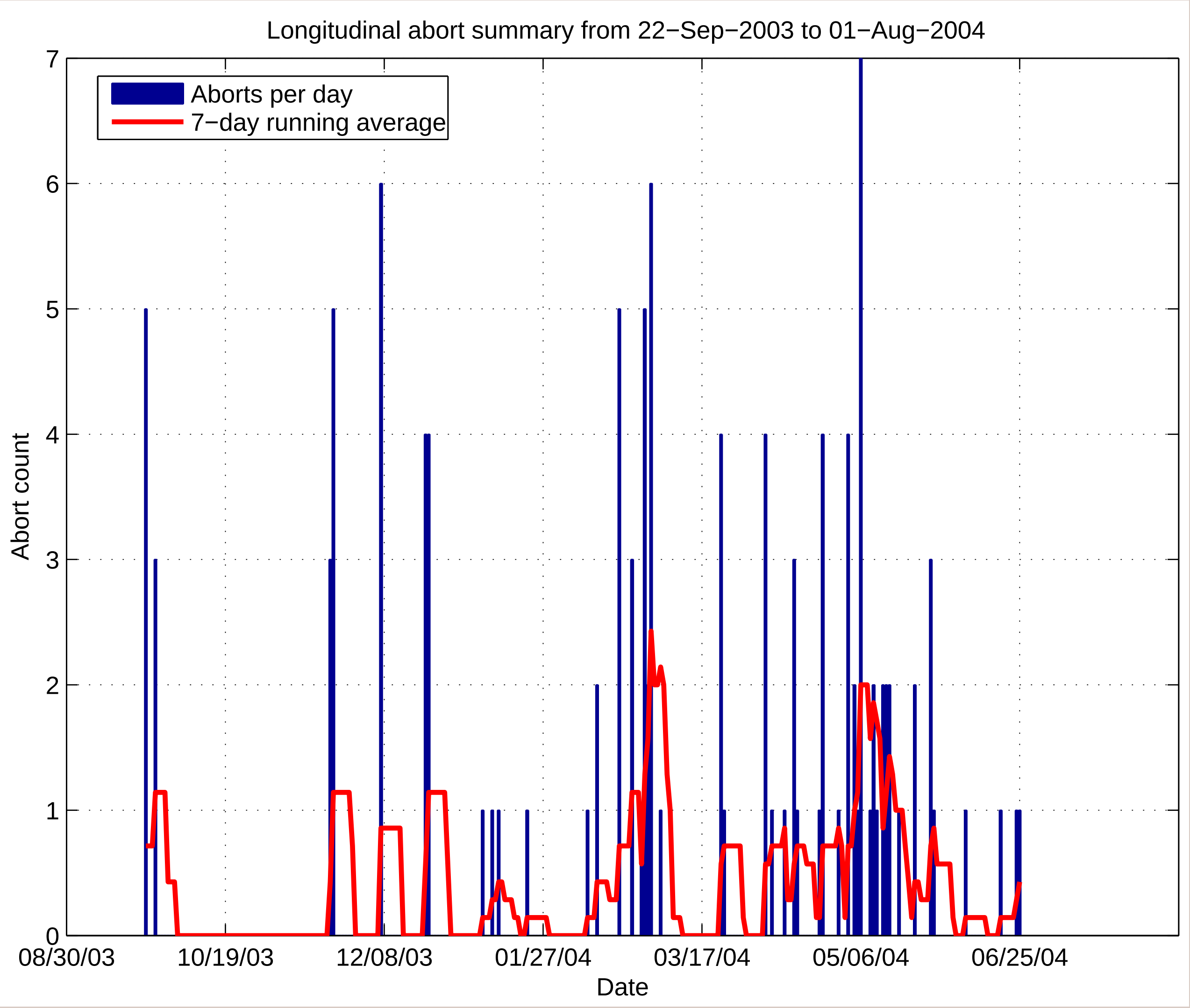
Jump in LER abort rate is more dramatic for several reasons: larger current increase, no low group-delay woofer

Beam aborts due to longitudinal instabilities: HER

Peak in the end of February is due to the damaged link cable picking up radiated RF in building 641.

Low group-delay woofer commissioned on 5/6. Abort rate peaks around that time due to the HER bumping against 1380 mA limit.

After several weeks of tuning the abort rate was reduced significantly despite higher beam currents.

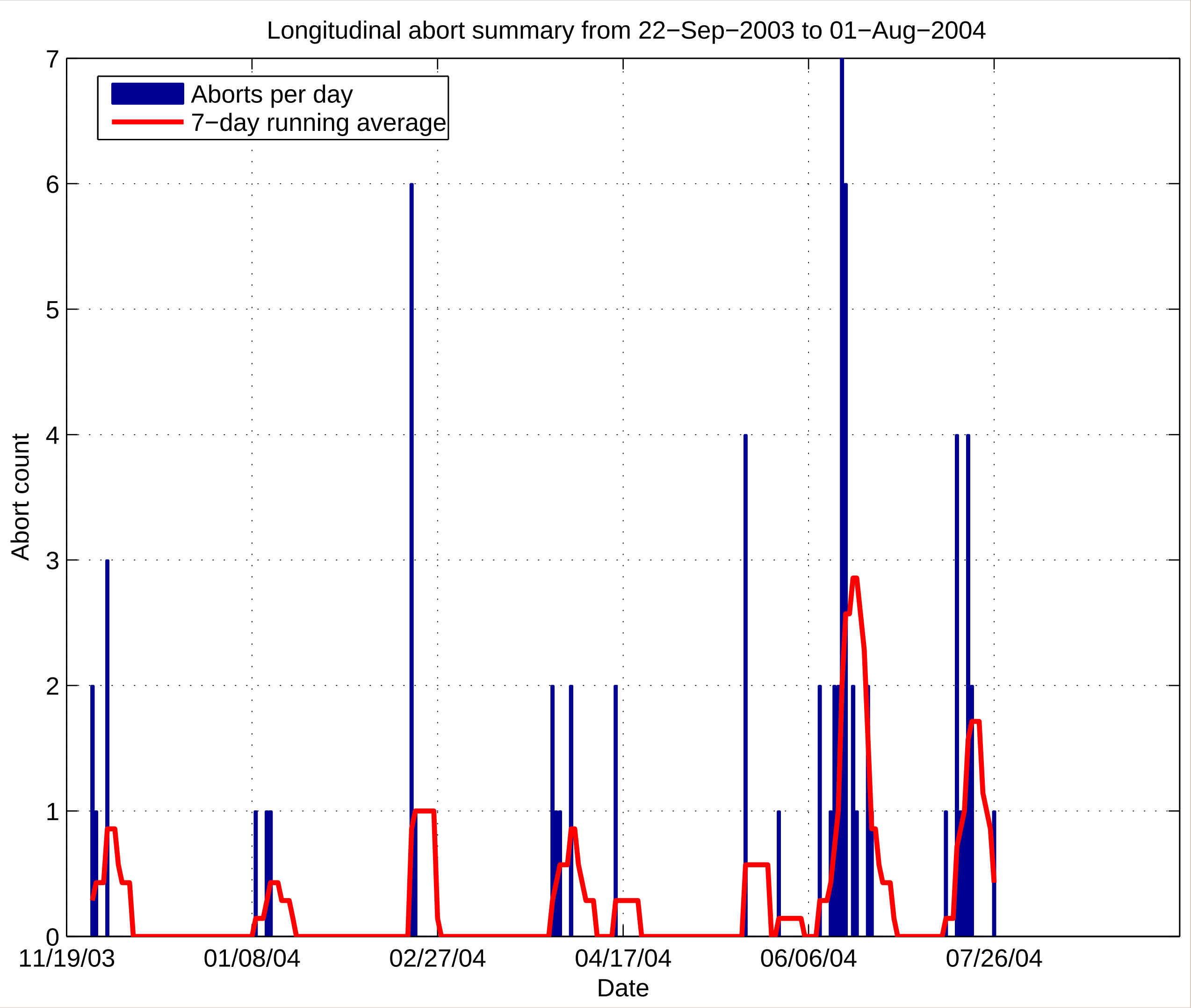


Beam aborts due to longitudinal instabilities: LER

Excellent performance until early June

Unexplained changes caused multiple aborts, no obvious culprits

LLRF tuning is critical, a rash of aborts in the late July is after 3 weeks without LLRF tuning. After large comb loop phase adjustments in 4-4 and 4-5 the abort rate went down.



Improvements in run 4

Introduced fault file analysis and abort classification

- leads to faster problem diagnosis and faster repair.

Actively used RF station phase tracking to maintain constant beam timing

- only needed to retime the LFB after the shutdown and when changing cables, amplifiers, etc.

Commissioned low group-delay woofer in the HER

- Pushed peak beam current from 1380 mA to 1590 mA
- Fewer aborts
- With LGDW loss of longitudinal control does not necessarily cause a beam abort

Introduced saturator daughter board in the existing comb modules

- Eliminated “stuck comb” bug

Created power balancing feedback to mask phase drifts in LLRF

Low group-delay woofer

A dedicated channel for controlling low-frequency modes. The correction signal is updated every revolution (wideband system updates every six turns). With the low group delay in the new processing channel higher feedback gains are possible leading to better damping of the fundamental-driven longitudinal eigenmodes

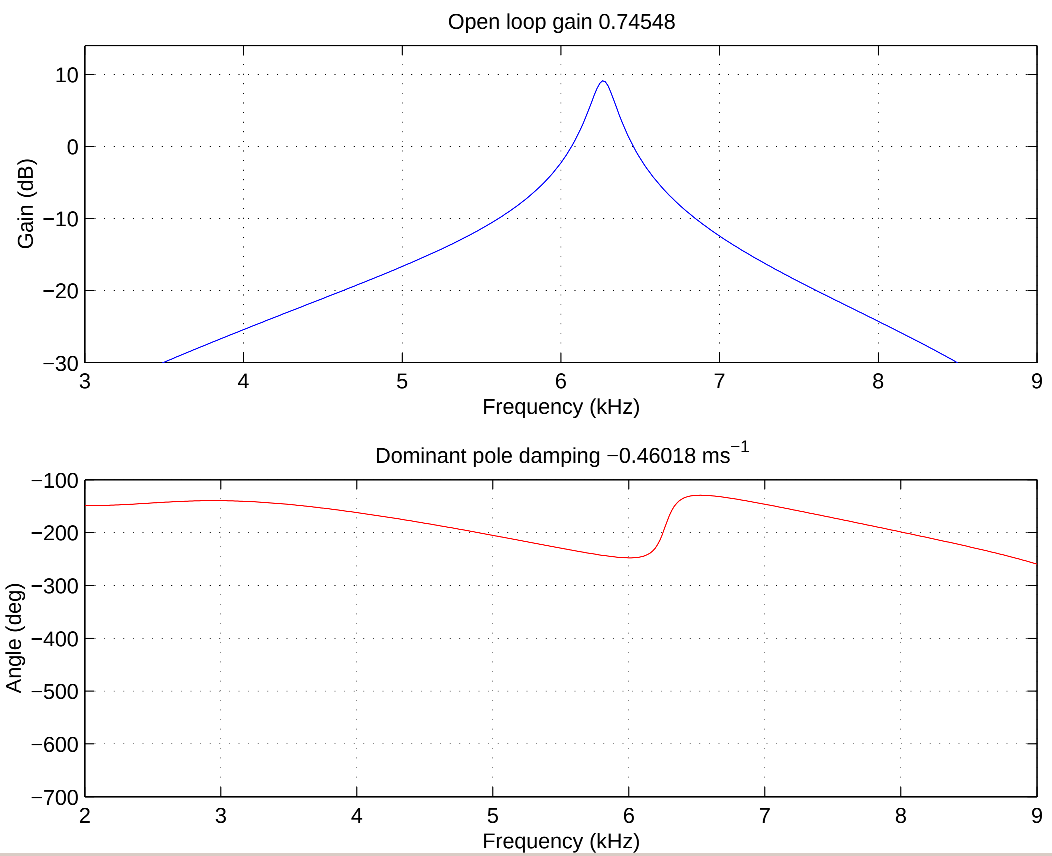
Why do we need a separate woofer processor?

Any feedback system is limited - concepts of minimum and maximum gain.

Minimum gain is important in instability control - below that value the system is unstable

Maximum gain is defined by the gain margin of the feedback loop. Above the maximum gain the system again becomes unstable.

Initially, as the loop gain is increased from the minimum value, the system becomes more stable (better damped).



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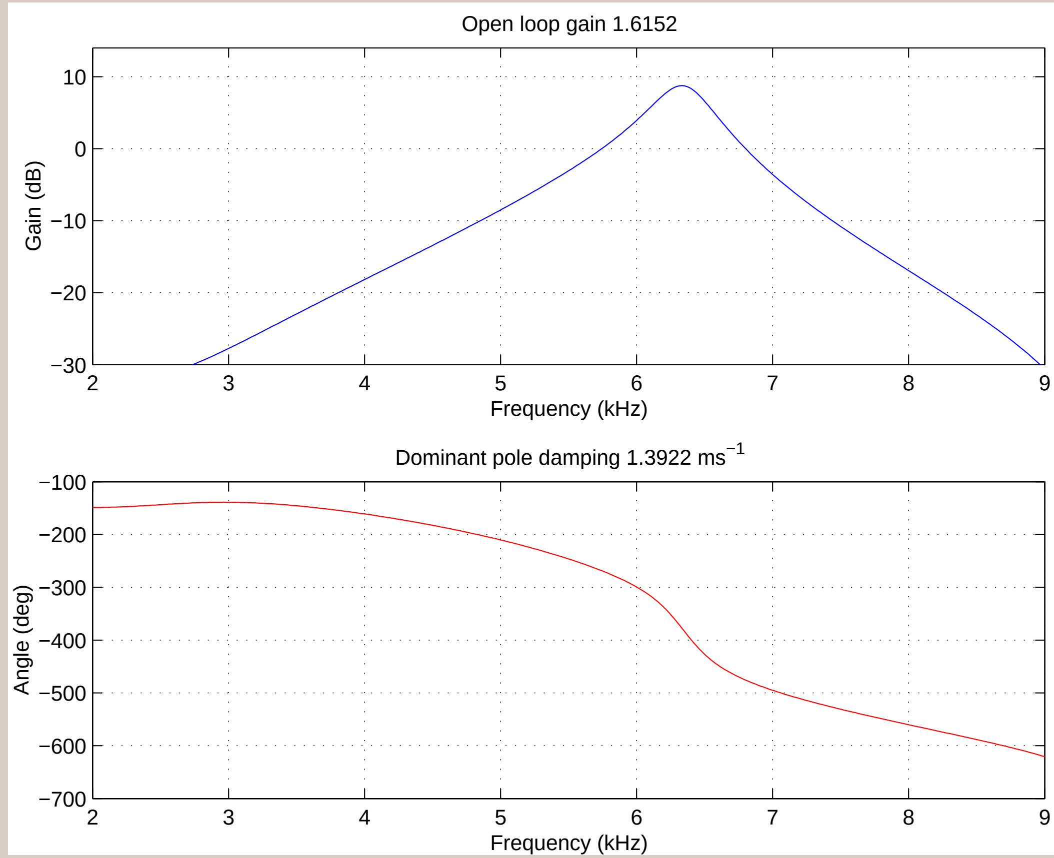

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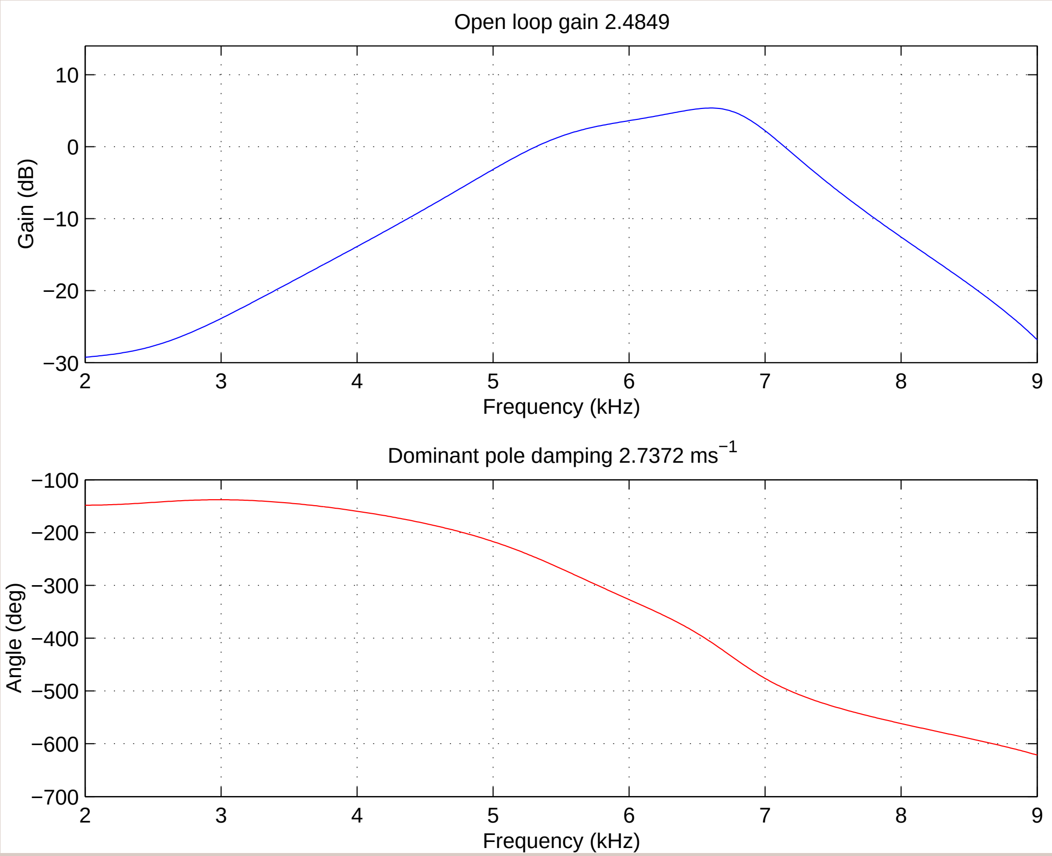

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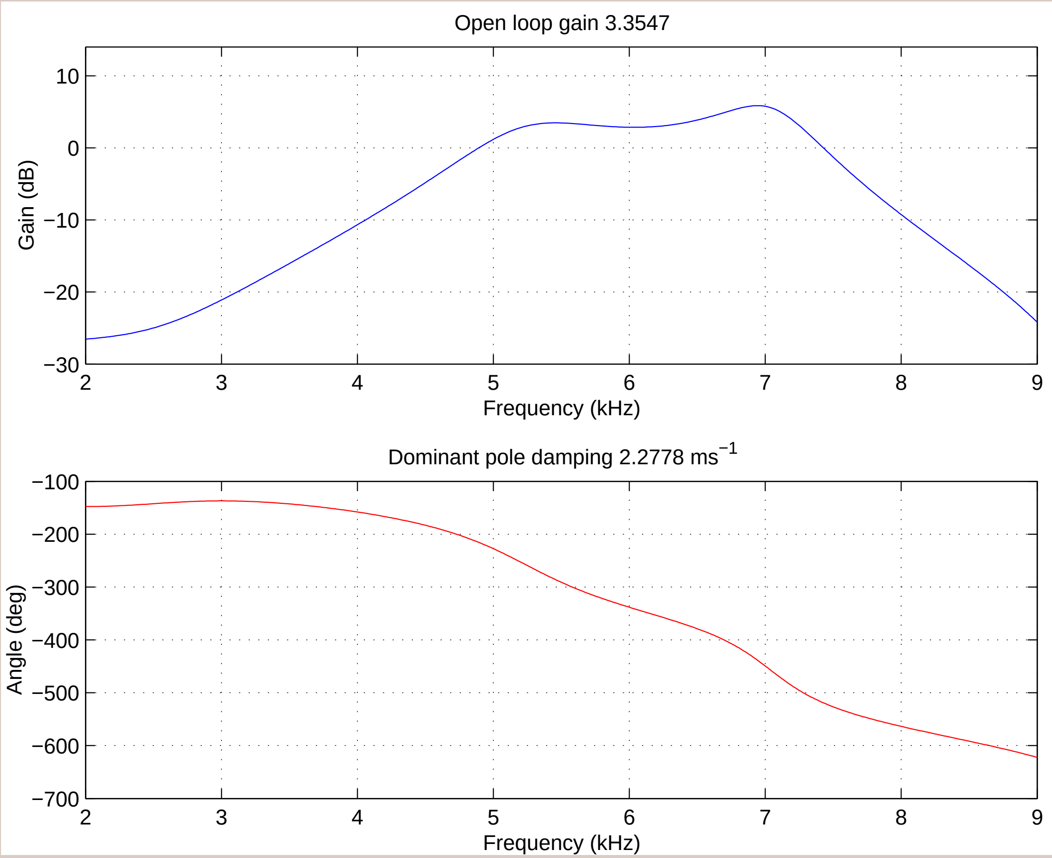

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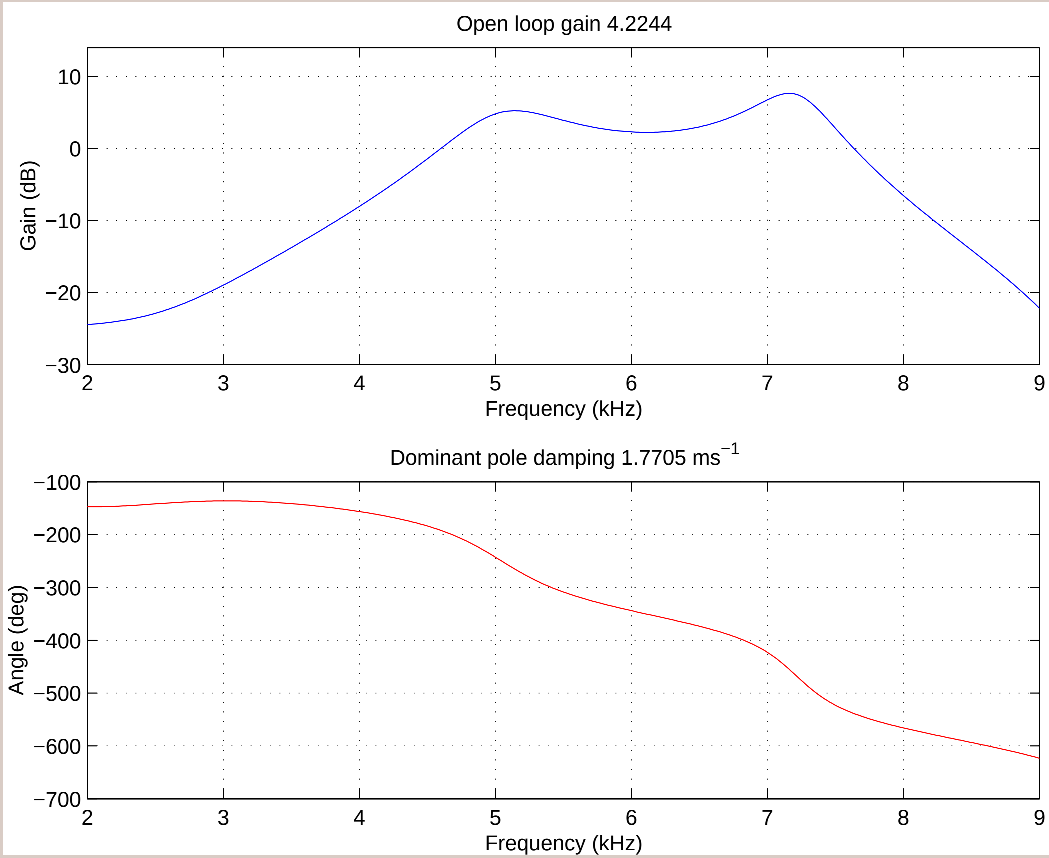

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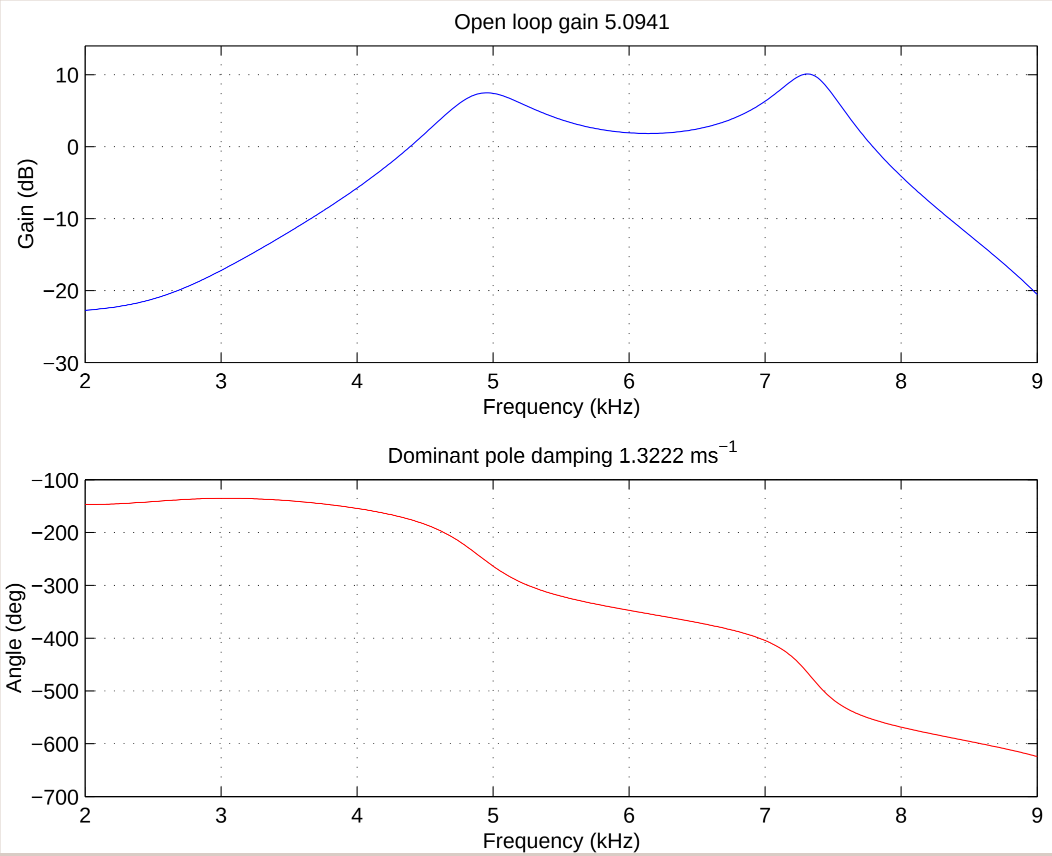

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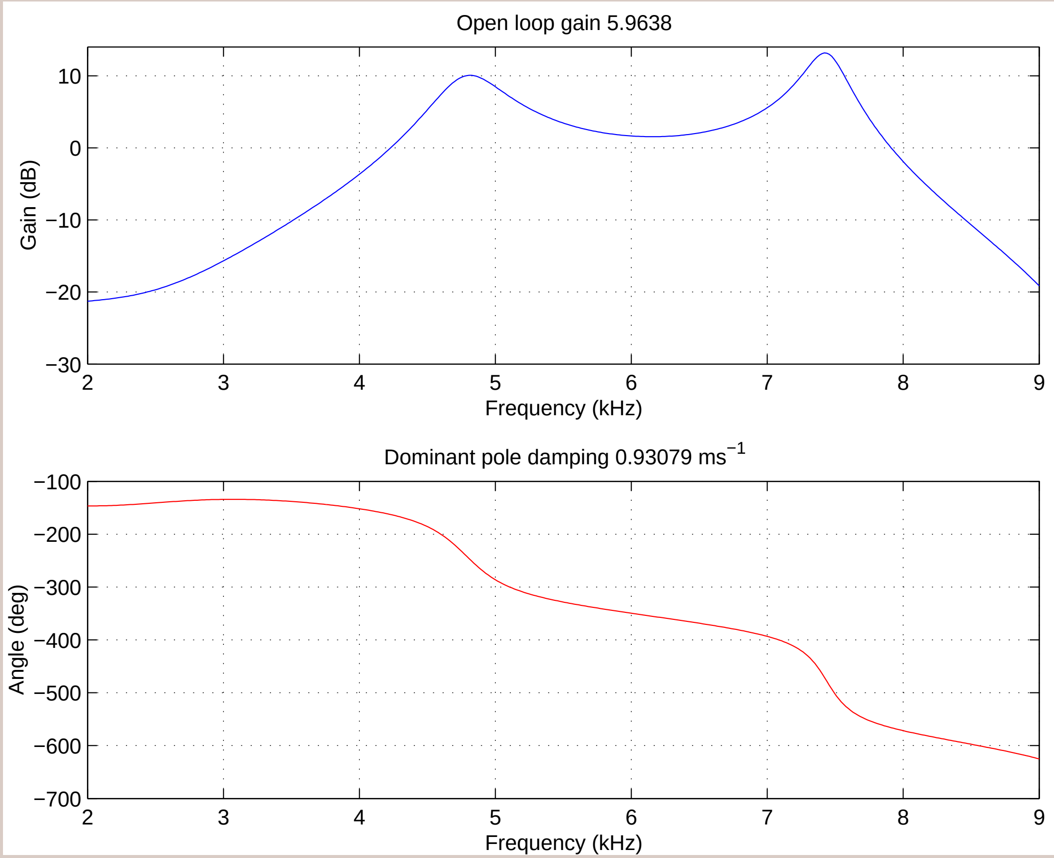

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Filter response: downsampled LFB

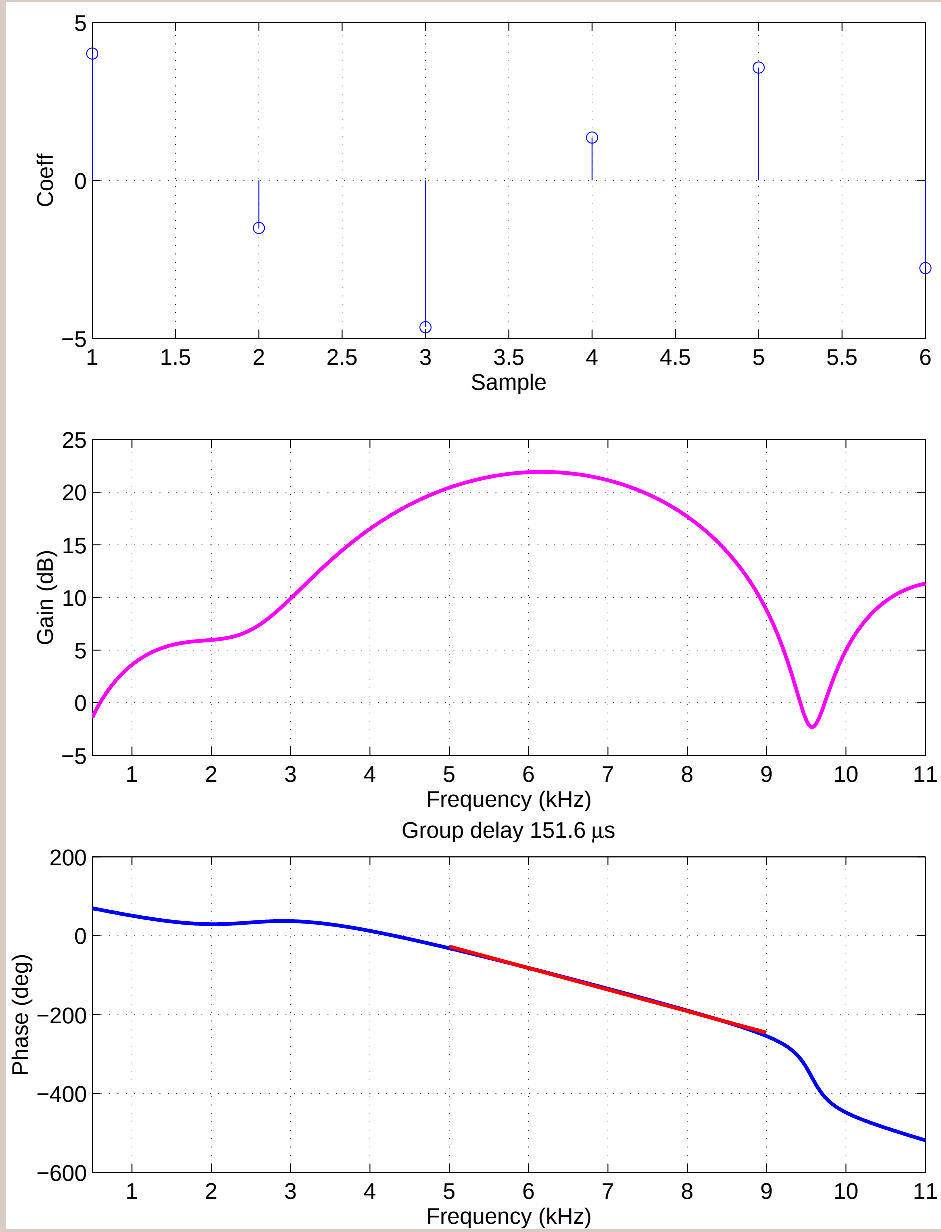
PEP-II LFB system processes bunch motion every 6 turns.

A 6-tap FIR filter has 3 taps * 6 turns = 18 turns of delay. With cable and sampling delays we get 152 µs

Relatively large phase slope around the synchrotron frequency leads to limited gain margins.

How can the situation be improved? Clearly, if we process beam motion on every turn the delay will be reduced. However the LFB has limited processing power and cannot do better than 6 turns of downsamping.

We have built a separate processing channel just for the woofer signal that computes corrections on every turn!



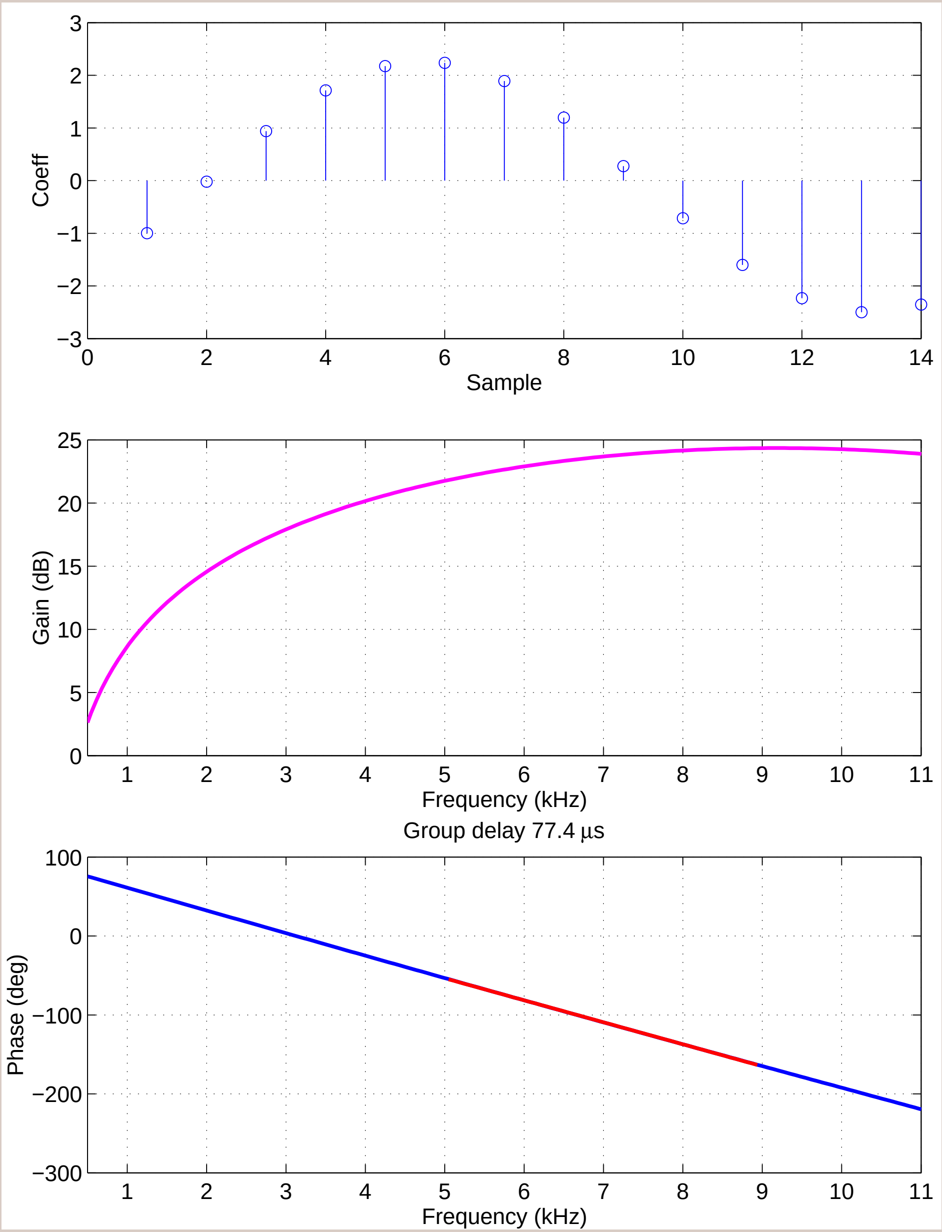
Filter response: low group-delay woofer

Group delay is reduced by a factor of 2

Note the wider filter bandwidth - directly related to a shorter time-domain response.

Still a very straightforward sampled sinewave design - more advanced filters need further work.

Note that LGDW processes the beam motion with 5 MHz bandwidth vs. 119 MHz for the LFB



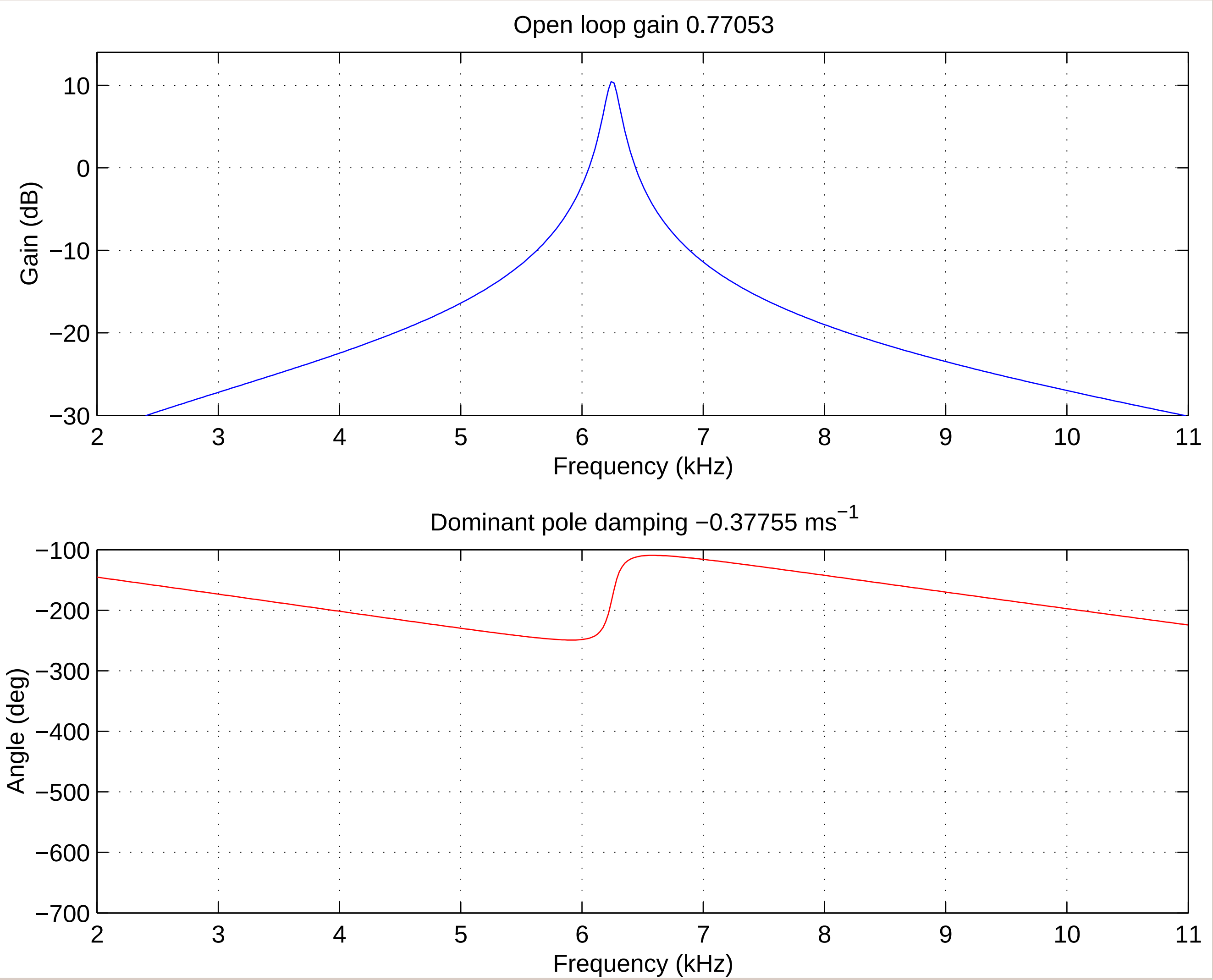
Damping provided by LGDW

With the lower group delay the new woofer can achieve much faster damping, than the LFB.

While the gain margin is an issue for both systems, the LGDW runs into the margin at higher loop gains

Due to lower group delay the closed-loop bandwidth is higher.

Peaking in the response happens further from the synchrotron frequency.



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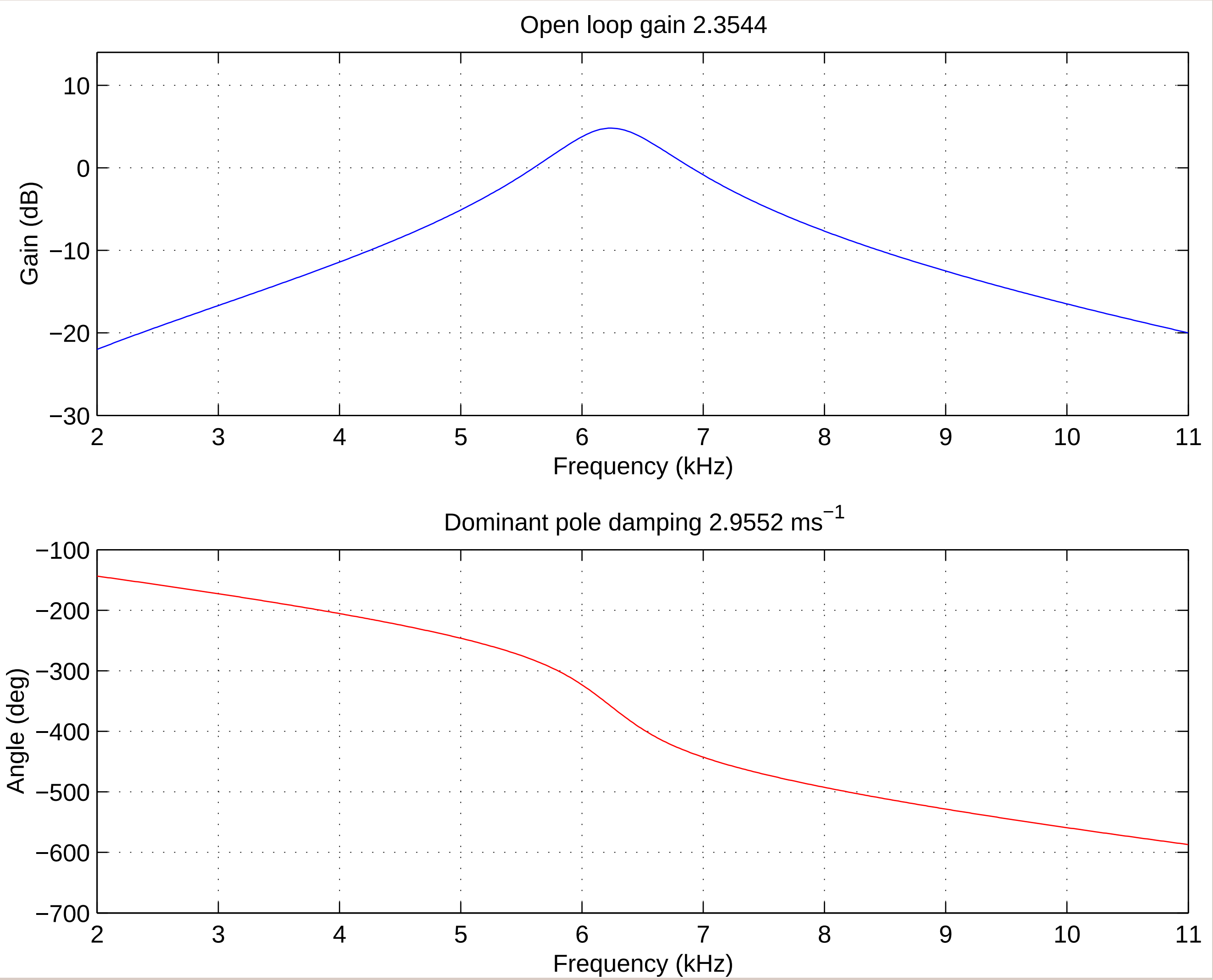

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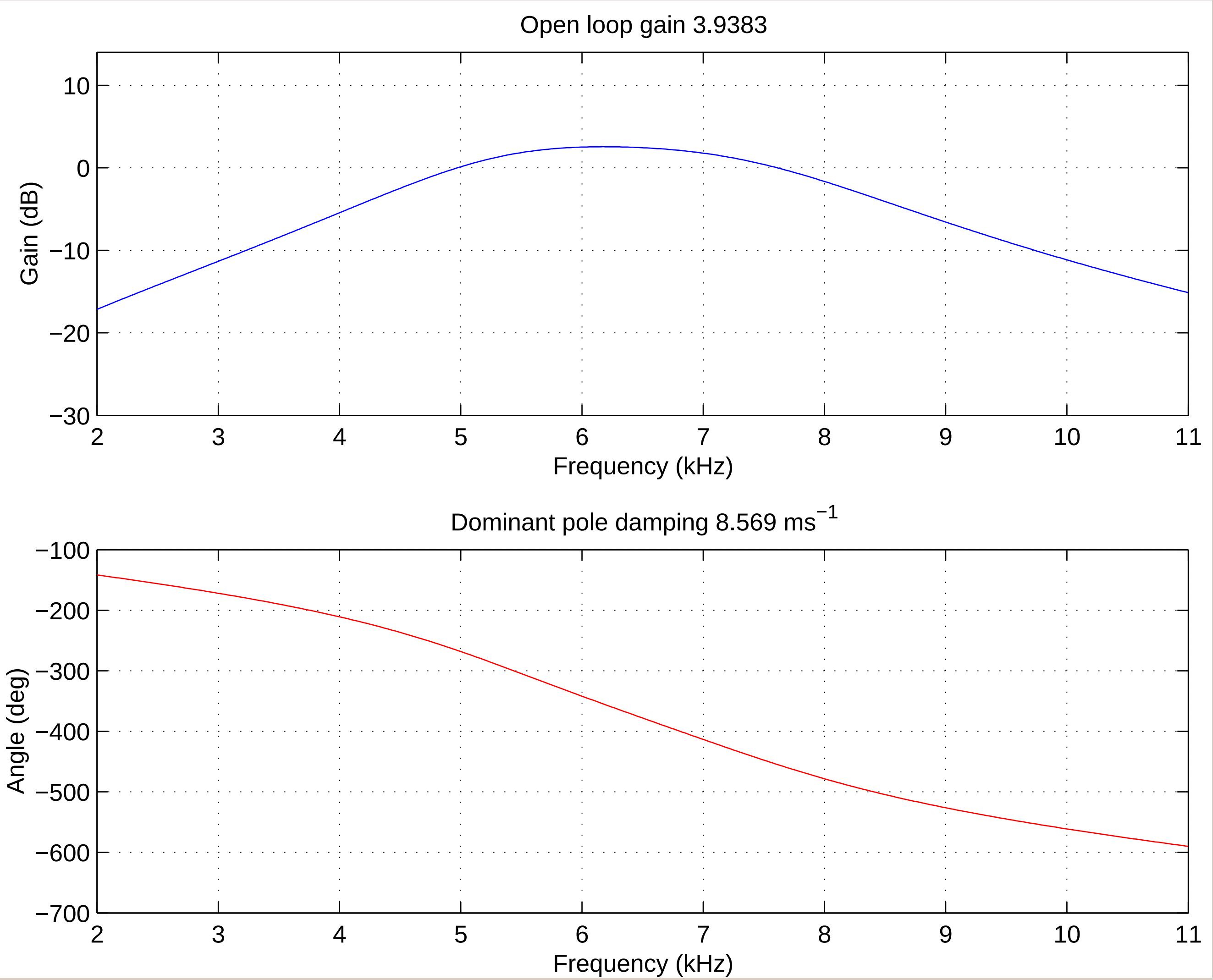

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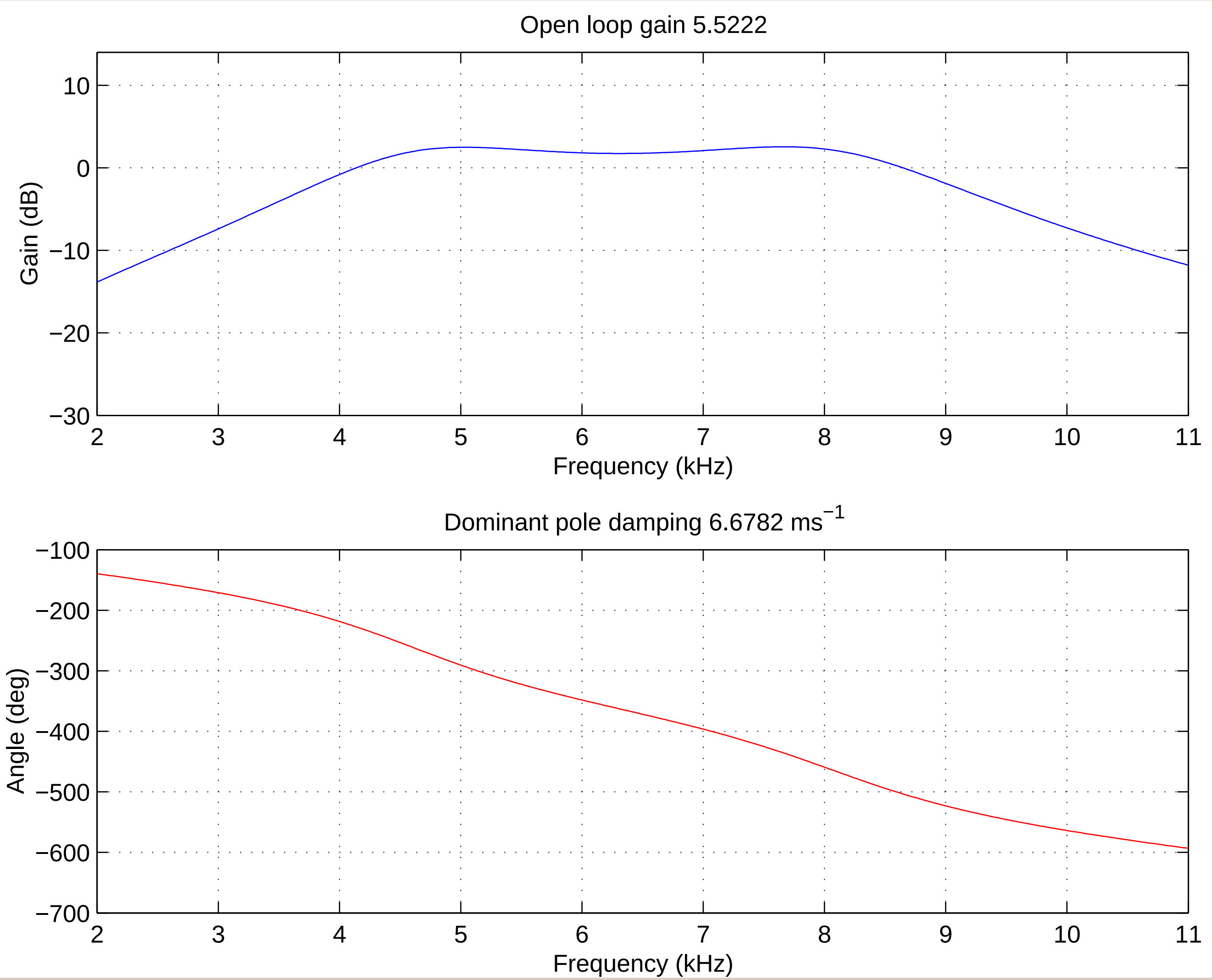

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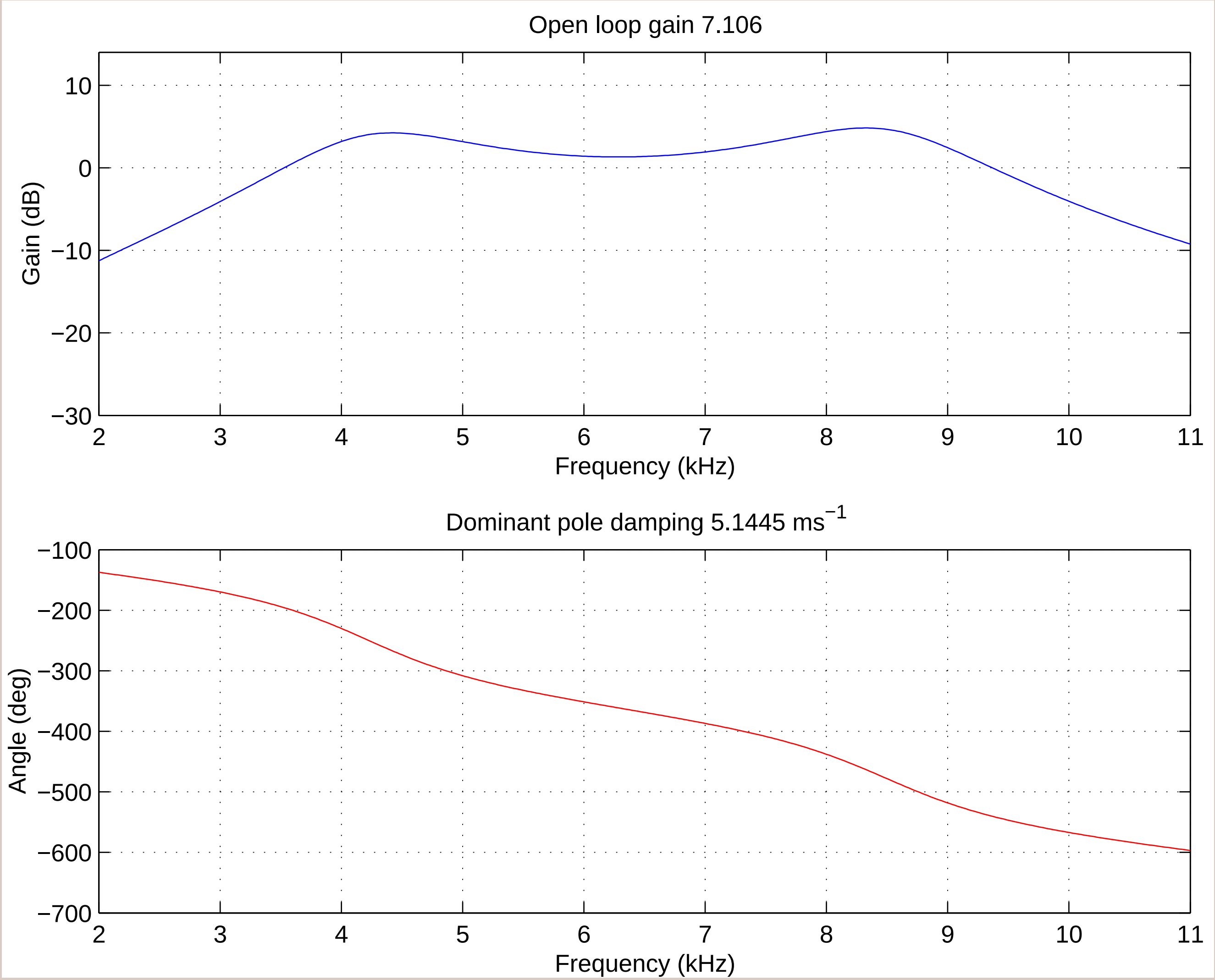

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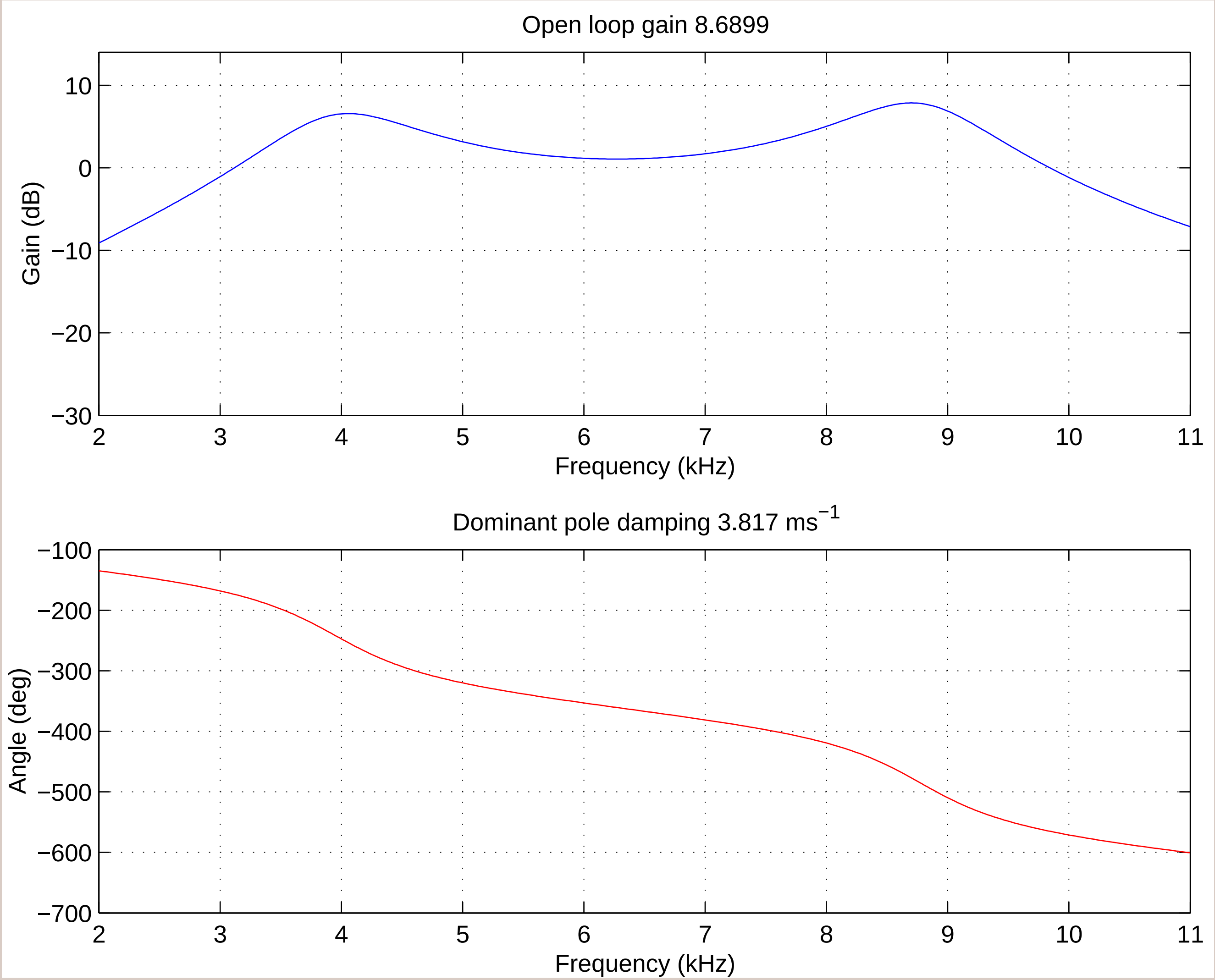

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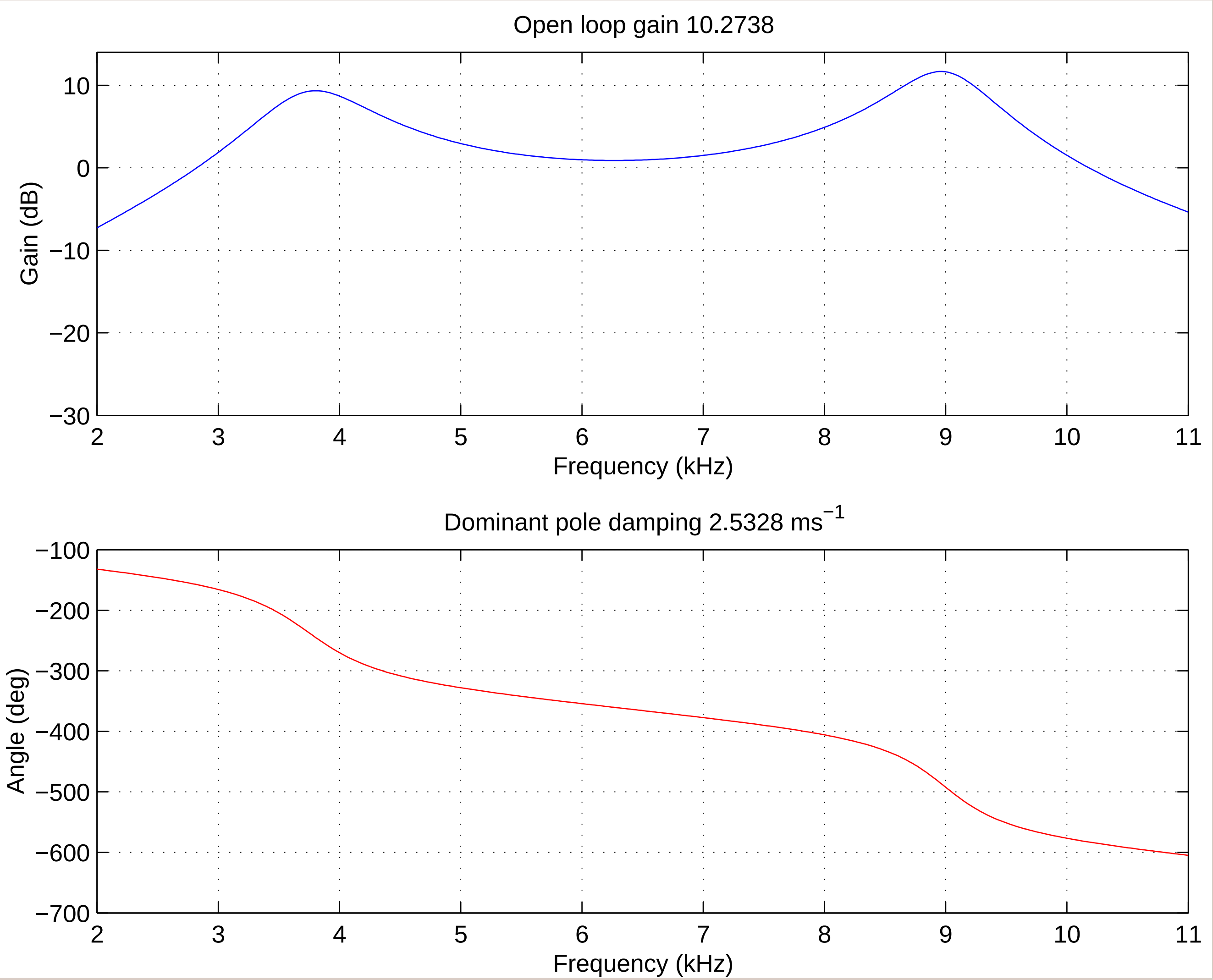

Results of LGDW prototype commissioning in the HER

Expected

- 1.5x to 2x improvement in damping of the low frequency eigenmodes
- A way to quantify the performance of the HOM damping
- Ability to significantly raise wideband feedback gain for better HOM control

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Unexpected

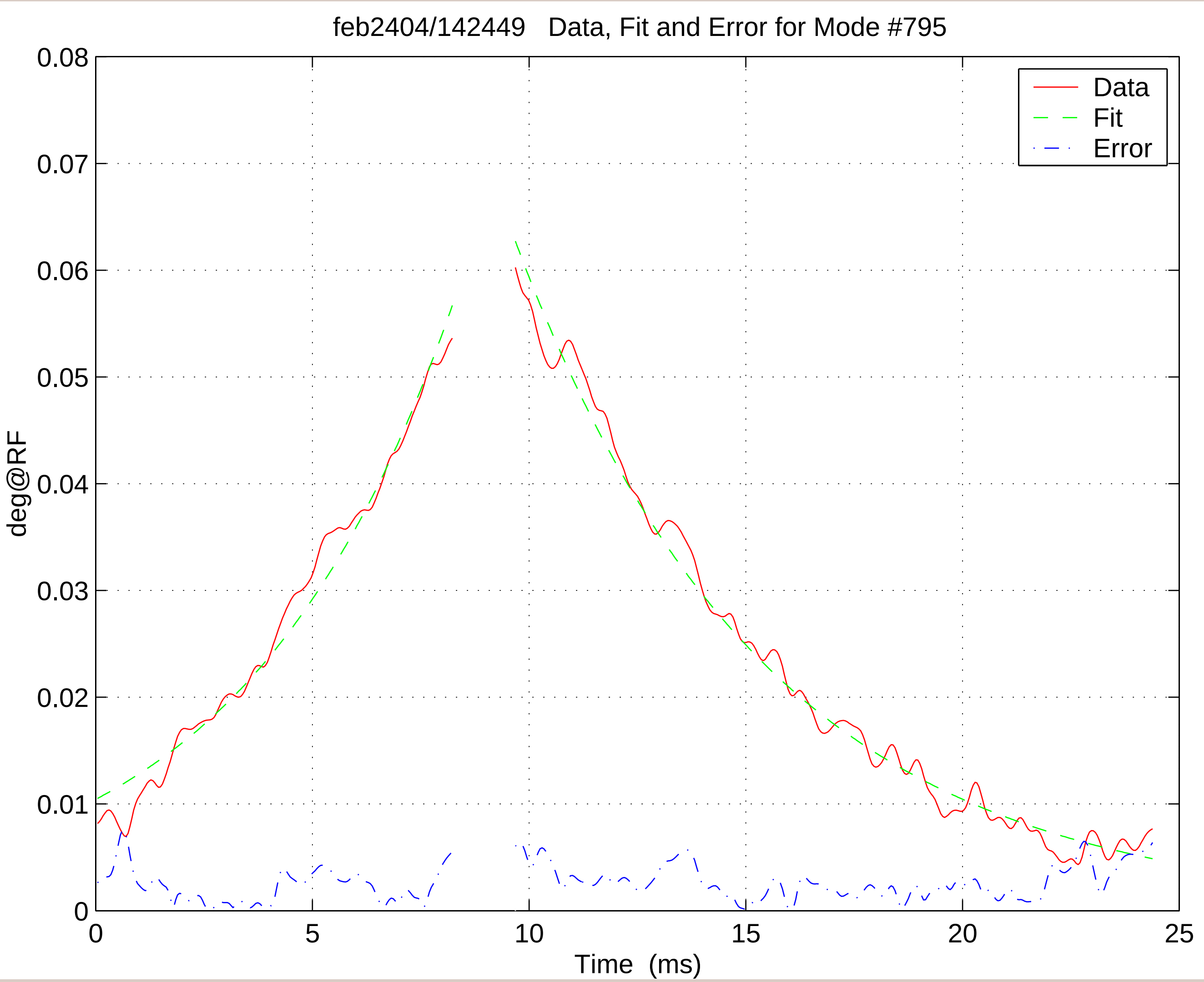
- There are very tight limits on the gain of the wideband LFB. The lower limit is set by the minimum gain necessary to damp the HOMs, while the upper limit comes from the high group-delay response of the LFB interacting with the highly damped low-frequency modes
- The loss of feedback control of the HOMs no longer causes beam abort. Wideband LFB can then be adjusted to suppress the beam motion. With the 2.5% gap we can reliably recapture the motion at the full HER beam current. With the 1.25% gap such recapture is impossible
- At the 2.5% gap tuning efficiency of the wideband LFB channel is improved dramatically - no need to refill the ring multiple times while adjusting the system.

Instability measurements during run 4: HER HOMs

Growth rate of 0.2 ms^{-1} and damping rate of 0.17 ms^{-1}.

Very little margin, especially at the nominal gain.

We expected that low group-delay woofer will allow to increase the gain for the broadband channel controlling the HOMs.



However the broadband channel affects both the HOMs and the low modes. As we increase the gain of this high group-delay channel the system runs out of gain margin for the low modes. Overall gain window is ~6 dB

Longitudinal instability modeling

Growth rates of the RF-cavity HOMs

- Pretty well understood, past measurements showed good agreement with cavity models and bench measurements. With the new low-group delay woofer we can carefully characterize these growth rates at high currents for better predictive accuracy.

Growth rates of the fundamental-driven eigenmodes

- These define, to large extent, the stability limits of PEP-II
- Need accurate modeling of RF systems and feedbacks to predict these rates
- We have restarted the modeling efforts with a new engineer (Claudio Rivetta) starting in January and a graduate student (Themis Mastorides) working on the model already.

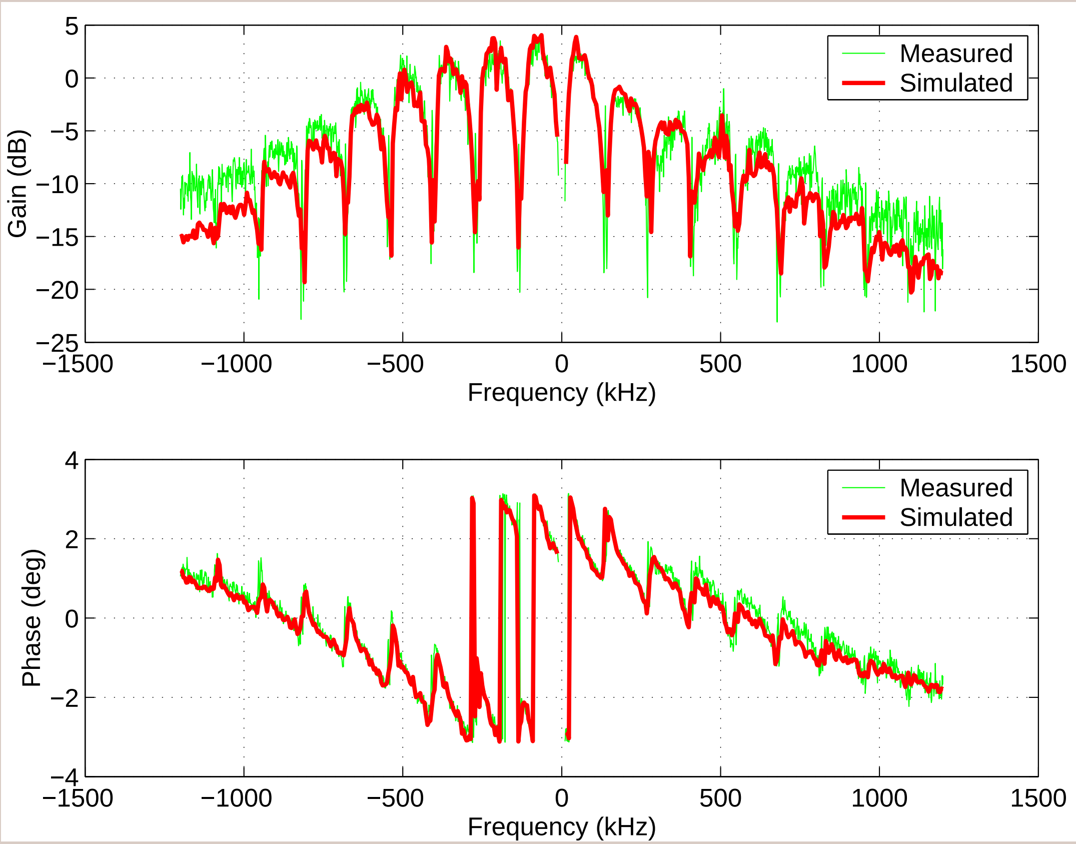
Feedback system performance, achievable damping

- We have a set of reliable models for the performance of the LFB and the low group delay woofer. These models were used to predict maximum LFB damping and expected improvements due to the LGDW

Development of time-domain RF system model

Main limitation in predicting longitudinal stability at higher beam currents is the uncertainty in estimating the growth rates of the fundamental-driven eigenmodes

Impedance reduction via the LLRF feedback loops is critical, however the real-life performance of these loops is difficult to predict due to klystron saturation.



Recent efforts

- Brought the time-domain model into agreement with the current RF system topology.
- As a test run the time-domain model using parameters extracted from an RF station transfer function measurement
- Transfer function extracted from the time-domain simulation data agrees very well with the transfer function of the physical station.

Limiting factors

LER

At the top currents (2300+ mA) longitudinal stability is very sensitive to small, uncontrolled changes in LLRF/LFB configurations. The exact cause is still unknown.

Commissioning of the low group-delay woofer in the LER will help in both improving the stability and in diagnosing the changes in configurations.

HER

Even with the low group-delay woofer we will run out of control around 1700 mA.

In order to get to higher currents we either need to reduce the growth rates or to improve damping.

Growth rate reduction might be feasible with linearizers which are still far from being ready for production (next talk by Dan Van Winkle).

To improve the damping we need a low group-delay broadband channel (processing of all bunches on all turns). As of now the only feasible option for such processing is the Gboard. We expect to have a prototype modules in April.

Summary

During run 4 improvements in the LLRF and LFB tuning allowed us to stably operate at much higher currents than in run 3.

Commissioning of the low group-delay woofer has been critical to increasing HER beam currents and reducing the number of longitudinal instability aborts.

LGDW is badly needed in the LER - commissioning is planned for the fall

An unexpected result of the low group-delay woofer commissioning in the HER is that in the dual-channel configuration (LGDW and the wideband LFB) the stability limitation comes from the LFB due to its high group delay.

To further improve damping and push HER currents beyond 1700 mA we will need a completely new wideband processing channel capable processing every bunch on every turn (Gboard).

We are actively pursuing the modeling of RF systems to be able to accurately predict the longitudinal stability margins in different configurations.