RF and feedback system status

Dmitry Teytelman

Outline

1 Coupled-bunch instabilities in PEP-II

2 Stability in transverse planes: TFB status

3 Longitudinal stability: LFB status

4 Fundamental impedance of PEP-II RF cavities and longitudinal stability

5 Low-level RF control

6 Longitudinal instability growth rates and klystron saturation

7 Limitations of the longitudinal feedback

8 Proposed RF upgrades and preliminary analysis

9 Summary
PEP-II is designed to operate above instability threshold in all 3 planes: horizontal, vertical and longitudinal.

Beam is kept stable via a combination of three techniques

- HOM damping in RF cavities - longitudinal and transverse
- Bunch-by-bunch feedback systems - longitudinal and transverse
- Active impedance reduction for the fundamental mode of the RF cavities - longitudinal
Coupled-bunch instabilities: eigenmodes and impedances

For an even fill pattern the bunch motion can be easily projected into the even-fill eigenmode (EFEM) basis. For $N$ coupled harmonic oscillators (bunches) there are $N$ normal modes.

Longitudinal modal eigenvalues are given by

$$\Lambda_l = -d_r + i \omega_s + \frac{\alpha e f_{rf}}{2 E_0 v_s} I_0 Z_{\text{eff}} \left( l \omega_{\text{rev}} + \omega_s \right)$$

$$Z_{\text{eff}}(\omega) = \sum_{p = -\infty}^{\infty} \frac{(p \omega_{rf} + \omega)}{\omega_{rf}} F(p \omega_{rf} + \omega) Z(p \omega_{rf} + \omega)$$

Real part of the eigenvalue is the exponential growth rate, imaginary part - undamped natural frequency.

Growth rate is proportional to beam current. Above some threshold current the system is unstable.

Two ways to fight the instabilities: lower the impedance via passive or active techniques or apply feedback damping

Form factor $F(\omega) = e^{-\left(\omega \sigma_z\right)^2}$ defines roll-off of the aliased impedance due to non-zero bunch length.
Transverse feedback status

PEP-II transverse bunch-by-bunch feedback systems provide sufficient damping to control HER at currents up to 1190 mA, LER - up to 1400 mA (2430 mA in collision).

Reliability issues:

Output amplifier power supply failures

We keep burning up the $\pi$ filter protecting the LER Y- power amp - measure beam-induced power.

Heating of kicker electrodes

• New kicker is being designed

Sensitivity to beam timing

• Hardware failure in the processing channel is suspected; it is being investigated.

Machine development plans: measurement of transverse growth and damping rates in LER using the HER longitudinal feedback system hardware.
Longitudinal feedback status

Detection at $6 \times f_{\text{rf}}$ (2856 MHz), correction at $9 f_{\text{rf}}/4$ (1071 MHz).

Processing array of 80 DSPs, $3.2 \cdot 10^9 \text{MAC/s}$

Sampling at 238 MHz with processing of up to 1746 bunches.

Downsampling to reduce computational load.
LFB operational issues

Set and forget mode of operation, only needs adjustments if RF reference shifts.

Digital processing and analog front/back ends - high reliability, very few problems

Reliability issues

Power amplifier failures

- Most failures are in amplifier power supplies
- Running configuration has been optimized to provide a spare amplifier which can be quickly placed online - we now run on 6 amplifiers, one spare
- Another spare amplifier has been ordered - will allow 7 amplifier kicker drive configuration

Kicker heating

- A new, Frascati-style (damped cavity) kicker has been designed and is being manufactured. Planned installation - December 2003.

Feedthrough and cable failures - high beam induced power in the present kickers (load ports) leads to connector and cable failures.

- Eliminated cables and monitor couplers by mounting the water-cooled loads directly on the feedthroughs
- New kicker will couple less power and in a narrower band of frequencies
Consider only the fundamental mode of the RF cavity - non-negligible impedance only near $\omega_{rf}$

$$\Lambda_l \approx \Lambda^0 + \frac{\pi \alpha e f_{rf}^2}{E_0 h \omega_s} I_0 [Z(\omega_{rf} + l \omega_{rev} + \omega_s) - Z^*(\omega_{rf} - l \omega_{rev} - \omega_s)]$$

The growth rate is proportional to the difference of impedance real part at the upper synchrotron sideband of the appropriate revolution harmonic and the lower sideband of the opposite rev. harmonic.

When cavity detuning is near $\omega_{rev} - \omega_s$ peak of the cavity impedance (real) excites eigenmode -1.

For PEP-II beam loading is high enough that RF cavities must be detuned beyond first revolution harmonic. The worst-case growth rate for mode -1 is 30 ms$^{-1}$. Compare 33 $\mu$s growth time to 185 $\mu$s synchrotron period!

Unlike higher-order mode resonances the fundamental mode cannot be suppressed by passive measures and require active feedback.
The most important elements of the impedance controlling feedback loops are shown. The direct feedback loop uses the cavity vector sum signal (a complex signal), scaled in magnitude and rotated in phase as an input to a reference summing node. The comb loop (a periodic IIR filter) uses the direct loop output via the comb filter, scaled and rotated, as a summing input. The adjustment of the direct loop gain and phase, and the adjustment of the comb loop gain and phase, are critical to achieving feedback loop stability and impedance control.

The overall action of the topology is to keep the combined direct and comb outputs exactly equal to the station reference - any error signal is amplified via the klystron and cavity path. The overall station cavity magnitude and phase is set via this reference. Not shown are many elements (such as lead/lag compensation to improve the loop stability margin, an integrator for high DC gain, etc.)
Two feedback loops are used in PEP-II to reduce the fundamental impedance acting on the beam: direct and comb.

Direct loop is a proportional feedback loop around the cavity. Closing the direct feedback loop reduces the effective impedance seen by the beam and lowers the growth rates. However the rates are still too high.

To reduce the growth rates further we add the comb filter with narrow gain peaks at synchrotron sidebands.

Expected growth rates shown here are computed using a linear transfer function model of the RF feedback system.

According to the linear model the growth rate reduction is two orders of magnitude, from 30 to 0.35 ms\(^{-1}\).
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Why do we need the complex comb loop? Can’t we just crank up the direct loop gain to reduce the impedance?

The answer is: “Direct loop gain is limited by the group delay”. As we increase the gain the points of unity gain move further away from the RF frequency. Due to the phase slope, loop phase at these unity gain points moves closer to 0 degrees (positive feedback) at higher gain.

Higher gain erodes both gain and phase margins causing the residual impedance to peak up. From the plots it is clear that the lower is the group delay the higher is the usable direct loop gain.

Need for low group delay is the main reason for a hybrid feedback system with an analog direct loop channel.

The current system has RF input to output delay of 86 ns with approximately 3 MHz usable bandwidth. Sampling at 10 MHz - one cycle is 100 ns of delay!
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PEP-II direct loop: gain limits

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Growth rates are 10 to 15 times faster than predicted by a linear model!

Significant scatter in growth rates

One data point stands out with very large growth rate and significant tune shift - must be related to a transient event in RF impedance control.

Damping rates of the same order as growth rates - not a lot of control margin.

The feedback is set up near the maximum usable gain - higher gain does not produce more damping.
Limits on achievable LFB control

Instability growth rates

- Maximum stable loop gain - depends on controller design, total loop delay.
- Maximum usable loop gain - gain that provides the largest damping. Depends on the same parameters as the maximum stable gain, but is significantly lower.
- Feedback systems in PEP-II (both LER and HER) are currently running near maximum usable gain to control fundamental-driven modes.
- Noise floor at the ADC - depends on RF-driven noise level, not a problem for the PEP-II in the current configuration
- Transient sensitivity - effect of injection and RF feedback transients on longitudinal control. The sensitivity can be reduced by increasing kicker voltage.

Synchronous phase transients (gap transients)

- Front-end of the LFB uses a phase detector at 6th harmonic of the RF. Range of detectable signals is 180 degrees peak-to-peak at $6 \times f_{RF}$ (or 30 degrees peak-to-peak at RF).
Small signal modulation of cavity phasors

Suppose the beam undergoes longitudinal oscillation. On the phasor diagram that corresponds to the phase modulation of the beam current vector.

Here the case with high beam loading is illustrated - geometry varies as a function of beam current.

If the generator current is constant we get mostly a phase modulation of the total cavity current.

If a feedback system acts to maintain constant cavity voltage by maintaining constant $I_{\text{tot}}$ the generator current must be amplitude modulated.

Important conclusion: at high beam loading canceling longitudinal oscillations of the beam requires amplitude modulation of the klystron.
Limitations of cavity impedance control

Due to klystron saturation linear impedance model is not applicable.

Let’s consider transfer of small-signal amplitude and phase modulations through the klystron in saturation. Amplitude gain is significantly reduced while the phase transfer function is unaffected by saturation.

According to the cavity vector diagram, suppression of phase-modulation of beam current (longitudinal oscillations) requires mostly amplitude modulation of generator current.

Problem cannot be rectified by increasing the overall loop gain since effective feedback gain through the phase modulation path is not affected by saturation. Increased overall gain will cause instability (of the feedback loop) in that path.

For the HER at 1 A the growth rates rise from linear prediction of $0.12 \text{ ms}^{-1}$ to actual 1-1.8 ms$^{-1}$. 
Verification using time-domain model

To check the assumption that high growth rates are caused by klystron saturation we used time-domain simulator developed by R. Tighe. We used the klystron saturation model as programmed in the simulator - this model might be quite different from the klystrons in the ring.

We used the fill pattern without the gap - adding the gap changes the results slightly, but is much harder to analyze.

Growth rates modeled without saturation agree with those predicted by the impedance model (as they should).

With saturation the growth rates are much higher, reaching 0.7 ms\(^{-1}\).

We have measured 1 ms\(^{-1}\) at 1A in the HER. This is within 50% of the time-domain simulation estimate.
Comparison of growth rates at different klystron saturation levels

Measurements in the LER at two RF station configurations: high saturation (19 W drive power) and low saturation (6 W drive power).

At low saturation the machine was longitudinally stable at 500 mA. Low saturation growth rates could only be measured after reducing direct loop gain by 1 dB and comb loop gain by 10 dB.

All data is for mode -3.

Even after lowering loop gains by a large amount low saturation growth rates are 50% less than high saturation rates.
Power-supply ripple and klystron gain

High-voltage power supply has significant ripple.

Direct feedback loop acts to cancel the ripple by modulating the klystron drive signal so that the cavity voltage (and klystron output) is constant.

We see large ripple in the drive signal. That translates directly into loop gain variation from the klystron large signal gain ($V_{out}/V_{in}$) shift and the small-signal gain modulation on the saturation curve. Ripple also modulates feedback loop phase.

This loop gain and delay variation is large enough to cause the observed growth rate scatter.

Two possible ways to attach this problem:

1. Get rid of the power supply ripple.
2. Make klystron gain and phase loops have sufficient bandwidth to mask the ripple using the complex multiplier in series with the klystron.
RF system reliability and fault analysis

Statistics from daily analysis of all RF-related beam aborts.

RF-related events are defined as beam aborts described in the operations log as being caused by ring RF system or longitudinal instabilities. Analysis is based on fault files saved by RF stations during a beam abort event and is very time-consuming.

PEP-II was down for PPS work, machine development, hardware failures for a total of 6 days over this period.

Around 8 aborts per day. Once non-RF events are filtered out we get down to 6 aborts per day due to HER and LER RF systems.

This is not completely representative of normal running - very close to machine startup.

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### RF fault analysis over 14 days (09/22/2003 - 10/06/2003), 62 faults

<table>
<thead>
<tr>
<th>Last event</th>
<th>Count</th>
<th>Stations</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/05/2003</td>
<td>8</td>
<td>HR81</td>
<td>No cavity voltage regulation</td>
</tr>
<tr>
<td>10/04/2003</td>
<td>6</td>
<td>LR45(3), HR26(3)</td>
<td>Station phase jump (in RFP)</td>
</tr>
<tr>
<td>09/28/2003</td>
<td>6</td>
<td>LR43</td>
<td>Klystron saturation (HVPS dip?)</td>
</tr>
<tr>
<td>09/24/2003</td>
<td>5</td>
<td>her</td>
<td>Longitudinal instability (LFB tuning)</td>
</tr>
<tr>
<td>09/23/2003</td>
<td>5</td>
<td>LR43</td>
<td>Klystron filament current glitch</td>
</tr>
<tr>
<td>09/29/2003</td>
<td>4</td>
<td>HR26</td>
<td>12-6 drive rising before cavity signal signature</td>
</tr>
<tr>
<td>09/25/2003</td>
<td>4</td>
<td>HR83</td>
<td>Klystron or HVPS arc (RE reported)</td>
</tr>
<tr>
<td>09/27/2003</td>
<td>3</td>
<td>her</td>
<td>Longitudinal instability</td>
</tr>
<tr>
<td>09/29/2003</td>
<td>3</td>
<td>HR81(1), HR83(2)</td>
<td>Allen Bradley heartbeat</td>
</tr>
<tr>
<td>10/06/2003</td>
<td>3</td>
<td>HR21(1), HR26(2)</td>
<td>Klystron arc</td>
</tr>
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</table>

Top 10 events account for 47 faults (76%)

<table>
<thead>
<tr>
<th>Station</th>
<th>Faults</th>
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<tbody>
<tr>
<td>LR43</td>
<td>12</td>
</tr>
<tr>
<td>her</td>
<td>10</td>
</tr>
<tr>
<td>HR26</td>
<td>10</td>
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<td>HR81</td>
<td>10</td>
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<tr>
<td>HR83</td>
<td>6</td>
</tr>
<tr>
<td>LR44</td>
<td>4</td>
</tr>
<tr>
<td>HR25</td>
<td>3</td>
</tr>
<tr>
<td>LR45</td>
<td>3</td>
</tr>
<tr>
<td>HR85</td>
<td>2</td>
</tr>
<tr>
<td>her</td>
<td>1</td>
</tr>
<tr>
<td>HR21</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Faults</th>
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</thead>
<tbody>
<tr>
<td>HER RF</td>
<td>32</td>
</tr>
<tr>
<td>LER RF</td>
<td>19</td>
</tr>
<tr>
<td>HER other</td>
<td>10</td>
</tr>
<tr>
<td>LER other</td>
<td>1</td>
</tr>
</tbody>
</table>
Fault file analysis example: “RE” abort

Nice steady-state running with periodic gap transient.

After the last turn the beam does not arrive in the cavity after the gap - cavity charges up to high voltage.

Cavity phase shifts by a large amount as well.

Synchronization to the gap indicates that the abort kicker fired after the last recorded turn (around 5.212 ms).

When the beam disappears the cavity becomes mismatched to the generator and we get large reflected power. However, the primary event that causes the reflected power trip is the abort kicker firing.

Even if the error log shows reflected energy trip on a given station this signature means we need to look for a different source - bad cable connection (4-3 case), another abort source.
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**PEP-II RF upgrade plans**

<table>
<thead>
<tr>
<th>Ring</th>
<th>Date</th>
<th>I, mA</th>
<th>Number of bunches</th>
<th>Two cavity stations</th>
<th>Four cavity stations</th>
<th>Cavities</th>
<th>$V_{rf}$, MV</th>
<th>$\alpha$</th>
<th>$f_s$, kHz</th>
<th>$\sigma_z$, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>LER</td>
<td>7/2003</td>
<td>1800</td>
<td>1050</td>
<td>3</td>
<td>0</td>
<td>6</td>
<td>3.3</td>
<td>0.00123</td>
<td>3.6</td>
<td>12</td>
</tr>
<tr>
<td>LER</td>
<td>10/2003</td>
<td>2700</td>
<td>1450</td>
<td>3</td>
<td>0</td>
<td>6</td>
<td>3.6</td>
<td>0.00123</td>
<td>3.79</td>
<td>11.4</td>
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<tr>
<td>LER</td>
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<td>3600</td>
<td>1500</td>
<td>4</td>
<td>0</td>
<td>8</td>
<td>5.6</td>
<td>0.001</td>
<td>4.27</td>
<td>8.2</td>
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<tr>
<td>LER</td>
<td>12/2005</td>
<td>3600</td>
<td>1700</td>
<td>4</td>
<td>0</td>
<td>8</td>
<td>6.4</td>
<td>0.0009</td>
<td>4.33</td>
<td>6.4</td>
</tr>
<tr>
<td>HER</td>
<td>7/2003</td>
<td>1150</td>
<td>1050</td>
<td>1 (1)</td>
<td>5</td>
<td>22 (2)</td>
<td>11.2</td>
<td>0.00241</td>
<td>5.6</td>
<td>13</td>
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<tr>
<td>HER</td>
<td>10/2003</td>
<td>1600</td>
<td>1450</td>
<td>3</td>
<td>5</td>
<td>26</td>
<td>15.6</td>
<td>0.00241</td>
<td>6.54</td>
<td>11.1</td>
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<tr>
<td>HER</td>
<td>10/2004</td>
<td>1800</td>
<td>1500</td>
<td>5</td>
<td>4</td>
<td>26</td>
<td>18.2</td>
<td>0.0018</td>
<td>6.10</td>
<td>8.9</td>
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<tr>
<td>HER</td>
<td>12/2005</td>
<td>2000</td>
<td>1700</td>
<td>7</td>
<td>3</td>
<td>26</td>
<td>20.8</td>
<td>0.0018</td>
<td>6.53</td>
<td>7.1</td>
</tr>
</tbody>
</table>

Main changes relative to June 2003:

- Double the beam currents
- Double the gap voltages
- Reduce momentum compaction
- Relatively few new cavities
Station power requirements and gap transients

A study of per station power requirements and synchronous gap transients using new “large-signal operating point code”.

<table>
<thead>
<tr>
<th>Ring</th>
<th>Date</th>
<th>I, mA</th>
<th>$V_{rf}$, MV</th>
<th>Power per station, kW</th>
<th>Gap transient peak-to-peak amplitude, deg@RF</th>
<th>Maximum detuning, kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>LER</td>
<td>10/2003</td>
<td>2700</td>
<td>3.6</td>
<td>858</td>
<td>16.7</td>
<td>244</td>
</tr>
<tr>
<td>LER</td>
<td>10/2004</td>
<td>3600</td>
<td>5.6</td>
<td>863</td>
<td>18.9</td>
<td>283</td>
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<tr>
<td>LER</td>
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<td>3600</td>
<td>6.4</td>
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<td>248</td>
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<tr>
<td>HER</td>
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<td>968</td>
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<tr>
<td>HER</td>
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<td>990</td>
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</tr>
<tr>
<td>HER</td>
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<td>2000</td>
<td>20.8</td>
<td>1016</td>
<td>9.2</td>
<td>138</td>
</tr>
</tbody>
</table>

LER RF has been operated at cavity detunings up to 220 kHz - performance of impedance control loops degrades with larger detuning.

Currently one HER klystron is limited to 730 kW, four - to ~900 kW. Overall loss is 84 kW per station. There are plans to replace klystrons, however current 8 station configuration is challenging - we do not have necessary power; two SLAC klystrons in 12/2003 will help.

Shorter abort gap in LER (1.25%) will reduce gap transient to match HER.
Upgrade issues: longitudinal stability

HOM-induced growth rates

- Measured 0.16 ms\(^{-1}\) at 2 A with 4 cavities, 3 MV in the LER
- Estimated 0.1 ms\(^{-1}\) at 1 A with 20 cavities, 10.6 MV in the HER
- LER growth rates peak at 0.38 ms\(^{-1}\) in the 3.6 A, 5.4 MV, 0.001 momentum compaction case
- HER growth rates peak at 0.16 ms\(^{-1}\) in the 1.6 A, 15.6 MV case
- Not a problem in the proposed configurations since these rates are much smaller than those of the fundamental-driven modes. In the high-current tests in June 2003 HOM growth rates in the LER were controlled at estimated growth rates of 0.27 ms\(^{-1}\)

Fundamental-induced growth rates

- HER has the fastest growth rates - we do not have a model to predict residual fundamental-driven growth rates in a mix of 2 and 4 cavity stations.
- LER is acceptable if 6 dB klystron amplitude saturation is assumed, rates almost double for 12 dB saturation. Growth rate scatter of ±30\% has to be taken into account as well.
PEP-II upgrades and fundamental-driven modes

Currently the situation is worst in the HER - LFB has very little control margin.

Going to 2 A we have

- 0.75 reduction in growth rates from momentum compaction change
- 1.18 increase due to larger number of active cavities (26 vs. 22)

Most important problem right now is that we do not have a reliable way to predict growth rates induced by the fundamental mode. Existing time-domain simulator (by Rich Tighe) does not allow to simulate a mix of 2 and 4-cavity stations. Even for a single station type the existing simulator is not true to the physical system.

Growth rates are extremely sensitive to RF setup and klystron operating point; to get reliable predictions need to accurately model the system.

Simple linear model shows residual impedance increasing with beam current - proportional scaling does not work.
Summary

Longitudinal and transverse feedback systems in PEP-II effectively suppress coupled-bunch instabilities due to higher-order modes, resistive wall, and RF cavity fundamental impedance.

Control margins and modeling of the longitudinal feedback has been extensively studied. Reliable offline models are available to evaluate system performance. Machine studies of the transverse growth and damping rates are needed to characterize the margins and to build an offline model.

In both HER and LER longitudinal modes driven by the residual fundamental impedance have the highest growth rates in existing as well as in upgraded configurations.

We have made a significant progress towards understanding PEP-II RF system operation and its limiting factors.

Klystron operating point has major impact on the performance of PEP-II LLRF impedance reduction feedback. It is possible to improve impedance control by lowering klystron saturation. How far klystron saturation can be reduced is determined by required power and collector dissipation limits. Klystrons capable of dissipating high collector power would help, but would require more collector cooling and line power.

Longitudinal control of fundamental-driven modes is near the limit. We hope to make progress by both improving the impedance reduction in LLRF and multibunch feedback control.

In order to confidently estimate PEP-II longitudinal stability in the upgraded configurations we need to develop proper simulation tools. We are actively working on this problem with support from LBNL and LNF-INFN.
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