Transient beam loading
FCC-ee (Z)

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FCC Week 2017
Outline

Introduction
  Beam Loading in Storage Rings
  Model Used

Beam Loading Simulations
  Gap Transients
  Detuning

Optimization
  Cavity Count
  Fill Pattern
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  Cavity Count
  Fill Pattern
Beam/Cavity Interaction

- RLC model of the accelerating cavity with two input currents: generator and beam;
  - Cavity voltage $\vec{V}_C$ is defined by the sum current;
  - Low loading ($\vec{I}_B \ll \vec{I}_G$) — cavity voltage is mostly defined by the generator current;
  - High loading — cavity voltage is strongly modulated by beam current;
  - Like to think of the interaction as a "feedback loop" — beam current source is affected by cavity voltage, while cavity voltage depends on the beam current.
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Why Worry about Beam Loading

- Two main effects of heavy beam loading:
  - Synchronous phase transients;
  - Longitudinal coupled-bunch instabilities driven by the RF cavity fundamental impedance
- Transient effects depend on
  - Total beam loading;
  - Fill pattern.
- Fill patterns can be designed to mitigate transient effects;
- But longitudinal instabilities due to the fundamental impedance remain an issue even with completely uniform fills;
- Reducing beam loading in the RF system design helps both issues.
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Phasor Diagram

- Phasors at RF frequency, cavity voltage on X axis;
  - Synchronous phase $\phi_B$ is determined by RF voltage, energy loss per turn;
  - For minimum generator power keep loading angle $\phi_L = 0$;
  - Cavity is detuned to maintain proper phase angle $\phi_Z$ between the total current and the cavity voltage;
  - PEP-II example: $I_B = 6$ A, $I_G = 1.7$ A;
  - To compensate fill pattern modulation, when $I_B$ goes to 0 in the gap, $I_G$ would need to match $I_T$!
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The Model

- Small-signal model developed by Flemming Pedersen;
- Model extended to include low-frequency coupled-bunch modes;
- Using reduced version that assumes no amplitude or phase modulation from the RF system.
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Synchrotron Frequency and Bunch Length

- Start from computing large-signal operating point (cavity detuning, RF power);
  - At that operating point, set up the small-signal model;
  - Compute $a_V$ and $p_V$ at 130680 points spaced by $T_{RF}$;
  - For each bunch calculate
    \[
    \omega_S^k = \sqrt{-\frac{\alpha e \omega_{RF}}{E T_0}} |V_k| \sin \phi_k
    \]
    \[
    \sigma_z^k = \frac{\alpha c}{\omega_S^k} \sigma_E
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Model Verification

- The model has been developed for ALS and PEP-II;
- PEP-II HER measurement and model output;
  - Reasonable overall agreement;
  - In the recent history, the model has been used to simulate BEPC-II transient behavior, more on that later.
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Parameters

- A. Butterworth, “Cavity design and beam-cavity interaction challenges”

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Energy</td>
<td>45 GeV</td>
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<tr>
<td>Energy loss per turn</td>
<td>36 MeV</td>
</tr>
<tr>
<td>Momentum compaction</td>
<td>$14.79 \times 10^{-6}$</td>
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<tr>
<td>Energy spread</td>
<td>$3.8 \times 10^{-4}$</td>
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<tr>
<td>Radiation damping time</td>
<td>414 ms</td>
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<tr>
<td>Gap voltage</td>
<td>255 MV</td>
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<tr>
<td>Harmonic number</td>
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<tr>
<td>Buckets filled</td>
<td>70760</td>
</tr>
<tr>
<td>$R/Q$</td>
<td>43.5 $\Omega$</td>
</tr>
<tr>
<td>$Q_0$</td>
<td>$2 \times 10^9$</td>
</tr>
<tr>
<td>Coupling factor$^1$</td>
<td>11784</td>
</tr>
</tbody>
</table>

$^1$Optimized for zero reflected power at 1390 mA
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Single Train

- Single train is unphysical;
- At 300 mA it is slightly more realistic;
- Bunch length is all over the place;
- As is the synchrotron frequency.
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Uniform Trains: 2 µs Abort Gap

- 66 trains of 1072 filled and 908 empty buckets (2.7/2.3 µs);
- 70752 filled buckets;
- Smaller phase transient, within reason — 47.9 ps peak-to-peak;
- 0.2% bunch length variation (peak-to-peak);
- Same range of variation for synchrotron frequency.
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Uniform Trains: 1 µs Abort Gap

- 135 trains of 524 filled and 444 empty buckets (1.3/1.1 µs);
- 70740 filled buckets;
- If gap transients are matched (two rings with identical fill patterns, RF, total currents), collision point shift is eliminated;
- Such matching is difficult to maintain in practice;
- 0.1% bunch length variation (peak-to-peak);
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That is 2.7 revolution harmonics;
Full loaded shunt impedance crosses 2 upper synchrotron sidebands;
Need aggressive RF feedback to manage longitudinal instabilities;
Without RF feedback longitudinal growth time is 1.3 ms (≈ 1/6 of the synchrotron period);
Modal tune shifts comparable to the synchrotron frequency.
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Optimizing Beam Loading, 400 MHz

With 88 cavities run 570 kW and 2.9 MV forward power and gap voltage per cavity;

Push to the limit: 56 cavities, 890 kW and 4.55 MV;

Transient is reduced;

Detuning is down to 1.7 revolution harmonics;

Not a big improvement overall.
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Summary
Single Bunch Train

- 0.3% gap (400 RF buckets, 1 µs);
- Uniform train of 65140 bunches with 5 ns spacing;
- Bunch length moves around by 3.4% (peak-to-peak).
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Fill Pattern Density Modulation

  - Charge removed from the gap is added symmetrically to both ends of the train;
  - 200 bunches removed from the gap;
  - Rather than double the charge, fill 200 buckets at the ends of the train in every bucket (2.5 ns) pattern;
  - Phase transient peak-to-peak amplitude is unchanged.
Fill Pattern Density Modulation

FCC-ee; 88/0 powered/parked cavities; $V_{\text{gap}} = 255$ MV; $I_0 = 1.39$ A; 65340 density mod fill

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![Graph showing bunch current over time](image1)

![Graph showing phase transient over time](image2)
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Fill Pattern Density Modulation (Continued)

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- All transients take place at the ends of the train;
- Mid-train there is very little synchronous phase variation;
- Bunch length varies by 0.01% peak to peak;
- Can uniformly spread additional bunches in the train to match the desired per bunch current (70758 bunch fill shown).
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How Does Fill Pattern Modulation Work?

- Two fill patterns used earlier:
  - 65140by2: one long train of 65140 bunches every other RF bucket and 400 bucket gap;
  - 65340 density mod: long train with density modulation.

- Both fill pattern spectra show notches at multiples of $h/400 \approx 327$ revolution harmonics due to identical 400 bucket gaps;

- Density modulation suppresses low-frequency revolution harmonics where cavity impedance is large.
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Does Fill Pattern Modulation Work?

- Measurements from the Advanced Light Source in Berkeley:
  - A train of 296 buckets, 32 bucket gap;
  - Buckets 1–16 and 281–296 filled to twice the charge.

- A bit of first revolution harmonic due to the detuned harmonic cavities;

- Measurements from BEPC-II in Beijing:
  - Half the ring filled (99 bunches, 4 ns spacing);
  - Partial compensation — 22 bunches at the ends filled to twice the charge.
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- Aggressive RF feedback loops will be needed to bring the longitudinal growth rates within the reach of the bunch-by-bunch feedback systems;
- Fill pattern uniformity is critical for achieving acceptable synchronous phase and bunch length transients;
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