Transverse machine impedance measurement in AGS and RHIC
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Measurements in AGS

Motivation:
Even if it is not an immediate concern, it is a good practice to keep an impedance model updated for each machine.

How?
Sacherer’s theory correlates the imaginary part of the global transverse impedance with the tune shift of mode-0 in the (Gaussian) bunch spectrum [1]:

\[ \frac{\Delta Q_0}{\Delta N} = \frac{-e^2 T_0}{4\sqrt{\pi} \gamma m_0 (2\pi)^2 Q_0 \sigma_z} \text{Im}(Z_{eff}) \]

Machine parameters:
- \( T_0 = 2.69 \text{ us} \),
- Average bunch length \( \sigma_t = 5.8 \text{ ns (1}\sigma\text{-rms)} \),
- \( Q_0 = 8.87 \text{ in V} \),
- \( \gamma = 25.38 \text{ (@Extraction)} \),
- \( R = \sim 128.45 \text{m} \rightarrow \text{slightly bigger than the PS} \).

NB: No multi-turn BPM system: only global measurements can be done

[1] See for example, Elias Métral, USPAS2009 course, Albuquerque, USA, June 22-26, 2009
Measurements in AGS

Bunch length (from Gaussian fit)

Y global Impedance: $Z_y = 1.3 \pm 0.1 \, M\Omega/m$

Y tune shift (per 1e11): $-5.145e-05$.

Very stable machine! → Measurements of very small tune shift possible!
Measurements in AGS

Y global impedance: \( Z_y = 1.3 \pm 0.1 \, M\Omega/m \)
Y tune shift (per 1e11): -5.145e-05.

In the past it was measured \( Z_\parallel(n)/n \sim 10\Omega \).

Assuming that the longitudinal impedance is mainly due to the resistive wall part, the transverse impedance can be estimated as:

\[
Z_y \cong \frac{2R}{b^2} Z_\parallel = 1M\Omega/m.
\]

Beam pipe radius \( b \cong 5\, \text{cm} \)

The longitudinal and transverse measurements are consistent!
Measurements in RHIC
Measurements in RHIC

Estimations:
• Estimation of localization accuracy.
• Estimation of L shape collimator impedance with NM code.

Measurements:

24-04-2013 (when I was there…)
• Chromaticity and BPMs set up in Blue.
• Few problems from power supply.
• 15’ of (fast!) measurements at injection in Blue ring.

01-05-2013 (operated by S.White and colleagues, thanks!)
• Chromaticity and BPMs set up in Yellow.
• Measurements at injection in Yellow ring.

15-05-2013 (operated by S.White and colleagues, thanks!)
• Chromaticity and BPMs set up in Blue.
• Measurements at injection in Blue ring to crosscheck the first results.
\( \sigma_t \sim 4.6 \text{ns} \)

\[ Z_x = 12.5 \pm 2.0 \text{ M}\Omega/\text{m} \]
Slope in X = -8.4e-4 +/- 1.4e-4

\[ Z_y = 11.1 \pm 1.5 \text{ M}\Omega/\text{m} \]
Slope in Y = -7.2e-4 +/- 0.9e-4

But… The tune drifts with time: it can be taken into account measuring at the same intensity after some time.
Blue - Tune shifts

After compensating...

\[
Z_y = (8.98 \pm 1.32) \ \text{M} \Omega / \text{m}
\]
Slope in Y is: \((-5.8 \pm 0.8) \times 10^{-4}\)

\[
Z_x = (10.7 \pm 1.9) \ \text{M} \Omega / \text{m}
\]
Slope in X is: \((-7.2 \pm 1.3) \times 10^{-4}\)

Crosschecked also on 15-05-2013:

\[
Z_x = (8.33 \pm 1.77) \ \text{M} \Omega / \text{m}
\]
Slope in X is: \((-5.50 \pm 1.17) \times 10^{-4}\)

\[
Z_y = (8.77 \pm 1.49) \ \text{M} \Omega / \text{m}
\]
Slope in Y is: \((-5.62 \pm 1.17) \times 10^{-4}\)

Measurements consistent with the uncertainty
Given a set of $M$ measurements of $\Delta \varphi$ with equal error bars $\sigma_{\Delta \varphi}$, obtained along an intensity scan $X$, we can calculate $\sigma_{\Delta \varphi}$ using a standard straight line least square formula:

$$\frac{\sigma_{\Delta \varphi}}{\Delta N} = \frac{\sigma_{\Delta \varphi}}{\sigma_X \sqrt{M}}$$

with $\sigma_X$ standard deviation of the intensity scan $X$.

Comparing with the previous formula one has:

$$\frac{1.12 \text{ NSR}}{\sigma_X \sqrt{N} \sqrt{M}}$$

$NSR = \sigma_n/A$: to be reduced.
(reduce noise level $\sigma_n$, increase betatron amplitude $A$, check BPMs gains, ...)

To be increased: $M=$ number of measurements. Usually a 100 points it’s the case.

To be increased: $N=$Number of turns. Depends on ability on hardware and data transmission from BPM to storage.

To be increased: It is the width of the scan of intensity. Upper threshold can be TMCI. Lower is BPM sensitivity.

*see IPAC13 - THOBB10*
Blue - Accuracy of phase advance slope

\[ \sigma_{\Delta \phi} = 1.12 \frac{\text{NSR}}{\sqrt{N} \sqrt{M}} \]

*Best performance*

\( I \sim 5 \times 10^9 \rightarrow 2 \times 10^{11} \)

\( M \sim 100 \)

\( N \sim 1000 \)

NSR* \sim 0.7%

\[ \sigma_{\Delta \phi} \sim 6 \cdot 10^{-5} \text{[rad/2\pi 1e-11]} \]

*Calculated for an amplitude \( A \sim 2 \text{mm} \) for full \( N \) turns coherent oscillation, and \( \sigma_n \sim 10 \text{ um rms noise from the BPM system.} \)
### Blue - Accuracy of phase advance slope

\[
\sigma_{\Delta \phi} \frac{\Delta N}{\Delta N} = \frac{1.12 \text{ NSR}}{\sigma_X \sqrt{N} \sqrt{M}}
\]

<table>
<thead>
<tr>
<th>Best performance</th>
<th>24-04-2013</th>
<th>15-05-2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I \sim 5e10 \rightarrow 2e11)</td>
<td>(I \sim 6e10 \rightarrow 2e11)</td>
<td>(I \sim 7e10 \rightarrow 1.7e11)</td>
</tr>
<tr>
<td>(M \sim 100)</td>
<td>(M \sim 29)</td>
<td>(M \sim 60)</td>
</tr>
<tr>
<td>(N \sim 1000)</td>
<td>(N \sim 380)</td>
<td>(N \sim 400)</td>
</tr>
<tr>
<td>NSR~0.75%</td>
<td>NSR~9%</td>
<td>NSR~7%</td>
</tr>
<tr>
<td>(\sigma_{\Delta \phi} \sim 6 \cdot 10^{-5})</td>
<td>(\sigma_{\Delta \phi} \sim 1.5 \cdot 10^{-3})</td>
<td>(\sigma_{\Delta \phi} \sim 10^{-3})</td>
</tr>
</tbody>
</table>

The loss of accuracy in the measurement is mainly due to:
- Short coherent time (<500 turns)
- High NSR.

By itself knowing the accuracy is not enough, we need an impedance amplitude to compare with, but it is good to keep it in mind.
Blue - phase advance slope

**Blue Y plane**
- Very noisy,
- Systematic offset?

**Blue X plane**
- Present oscillation on 15th, not on 24th. What was changed?
Yellow - Tune shifts

\[ \sigma_{z,\text{rms}} \approx 4.3 \text{ ns} \]

\[
\text{ZeffY: } (4.7299\pm 1.4513) \text{ MOhm/m} \\
\text{dQY/dN: } (-4.3001\pm 1.3194) \times 10^{-4} \\
\]

\[ \sigma_{z,\text{rms}} \approx 5 \text{ ns} \]

\[
\text{ZeffY: } (3.1411\pm 0.9046) \text{ MOhm/m} \\
\text{dQY/dN: } (-2.8557\pm 0.8225) \times 10^{-4} \\
\]

\[ \sigma_{z,\text{rms}} \approx 1.7 \text{ ns} \]

\[
\text{ZeffY: } (1.1549\pm 0.2041) \text{ MOhm/m} \\
\text{dQY/dN: } (-1.05\pm 0.1856) \times 10^{-4} \\
\]

\[ \sigma_{z,\text{rms}} \approx 4.3 \text{ ns} \]

\[
\text{ZeffX: } (2.2850\pm 0.5758) \text{ MOhm/m} \\
\text{dQX/dN: } (-2.1498\pm 0.5417) \times 10^{-4} \\
\]

\[ \sigma_{z,\text{rms}} \approx 5 \text{ ns} \]

\[
\text{ZeffX: } (4.2487\pm 1.8681) \text{ MOhm/m} \\
\text{dQX/dN: } (-3.9973\pm 1.7576) \times 10^{-4} \\
\]

\[ \sigma_{z,\text{rms}} \approx 1.7 \text{ ns} \]

\[
\text{ZeffX: } (5.3969\pm 1.3119) \text{ MOhm/m} \\
\text{dQX/dN: } (-5.0776\pm 1.2343) \times 10^{-4} \\
\]
Yellow – Accuracy of phase advance slope

\[
\sigma_{\Delta \phi} = \frac{1.12 \text{ NSR}}{\sigma_x \sqrt{N} \sqrt{M}}
\]

<table>
<thead>
<tr>
<th>Best performance</th>
<th>01-05-2013 #1</th>
<th>01-05-2013 #2</th>
<th>01-05-2013 #3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I \sim 5e10 \rightarrow 2e11 )</td>
<td>( I \sim 11e10 \rightarrow 2.4e11 )</td>
<td>( I \sim 9e10 \rightarrow 2.7e11 )</td>
<td>( I \sim 4e10 \rightarrow 2e11 )</td>
</tr>
<tr>
<td>( M \sim 100 )</td>
<td>( M \sim 50 )</td>
<td>( M \sim 16 )</td>
<td>( M \sim 40 )</td>
</tr>
<tr>
<td>( N \sim 1000 )</td>
<td>( N \sim 880 )</td>
<td>( N \sim 900 )</td>
<td>( N \sim 1000 )</td>
</tr>
<tr>
<td>NSR~0.75%</td>
<td>NSR~6%</td>
<td>NSR~4%</td>
<td>NSR~10%</td>
</tr>
<tr>
<td>( \sigma_{\Delta \phi} \sim 6 \cdot 10^{-5} )</td>
<td>( \sigma_{\Delta \phi} \sim 1 \cdot 10^{-3} )</td>
<td>( \sigma_{\Delta \phi} \sim 4 \cdot 10^{-4} )</td>
<td>( \sigma_{\Delta \phi} \sim 1 \cdot 10^{-3} )</td>
</tr>
</tbody>
</table>

Phase advance slope studies are still on going…
Conclusions and Outlook

Conclusions:

• **AGS:** The vertical impedance has been measured: $Z_y = 1.3 \pm 0.1 \text{ M}\Omega/m$. This is in good agreement with old measurements for the longitudinal impedance in the resistive wall approximation.

• **RHIC - Blue:** Tune shift and impedance measured: $Z_x = 9.5+/-1.8 \text{ M}\Omega/m$, $Z_y = 8.8+/-1.4 \text{ M}\Omega/m$. For the impedance localization: accuracy could be enough, at least for the horizontal plane, but the measurements appear to be very noisy.

• **RHIC – Yellow:** Tune shift and impedance measured: $Z_x = 3.9+/-1.3 \text{ M}\Omega/m$, $Z_y = 3.0+/-0.8 \text{ M}\Omega/m$. The impedance appears to be much less than Blue! Conclusions similar to the Blue hold for the localization.

Outlook:

• **AGS:** Horizontal plane will be measured as well (expected less impedance).

• **RHIC:** An estimation of some (big) impedance source could help understanding what impedance signal we want to localize. The resolution could be achieved by the good BPM system spending more energies on adjusting chromaticity.
BACKUP
24-04-2013 Amplitude and Noise
24-04-2013 Accuracy

(0.7%; 6e-5)
24-04-2013 Y phase advance

- 20% beating