Some RHIC & SPS MDs

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Outline

– Brief Introduction

– $\beta$-beating experiment (RHIC)

– Vertical impedance localization experiment (SPS)

– SPS e-Cloud experiments

– Long range beam-beam experiments

– LHC crab cavities

What/How Does One Measure?

\[ x(s) - \bar{x} = A\sqrt{\beta(s)} \cos(\phi(s) + \delta) + D_x(s)\delta \]
\[ \phi(s_1 \to s_2) = \frac{1}{\beta(s)} \int_{s_1}^{s_2} ds \]

†Some common techniques:
- k-modulation (\(\Delta Q = \frac{\beta}{4\pi} \Delta K\))
- Orbit corr (\(R_{ij} \approx \sqrt{\beta_i \beta_j \cos(|\phi_i - \phi_j|)}\))
- Freq analysis of turn-by-turn data
  - FFT‡, SVD, harmonic analysis
- Model independent analysis etc...

†See next AB seminar for more details (R. Tomás)
‡ Sussix, CERN SL/Note 98-017 (AP)
How Does One Measure?

Transverse Kickers

AC Dipoles

Beam Position Monitors

- Avg. Closed orbit
- Turn-by-turn data

\[ x \approx \frac{w}{2} \left[ U_+ - U_- \right] \]
Faulty BPMs & Noise
For example: RMS of Background to determine a faulty BPM

Several problems found at hardware & software level (lot of them fixed)
Spatial Filtering, using signal correlation

- Betatron signal is correlated around the ring
- $\Sigma_i$ largest peaks of the spatial vectors are used as observables
- Tune windows, model phase adv etc... can also be used to filter BPMs

Beta Beating & Correction

Quadrupole errors → β-wave:

\[ \frac{\Delta \beta}{\beta} \approx - \Delta k \beta_0 \sin(2(\phi - \phi_0)) \]

Correction (Global+Local):

\[ A_{ij} \Delta \vec{k}_j = \left[ \frac{\Delta \vec{\beta}}{\vec{\beta}} \right]_{1...i} \]

\[ \left| A \Delta \vec{k} - \frac{\Delta \vec{\beta}}{\vec{\beta}} \right|^2 = \text{min}, \quad \Delta \vec{k} = (A^T w A)^{-1} A^T w \left[ \frac{\Delta \vec{\beta}}{\vec{\beta}} \right] \]

Beta-bump (Local):

\[ \Delta q_1 = - \frac{\Delta \beta_2}{\beta_2} \frac{1}{\beta_1} \frac{1}{\sin(2\psi_{21})}, \quad \Delta q_2 = + \frac{\Delta \beta_2}{\beta_2} \frac{1}{\beta_2} \frac{\sin(2\psi_{31})}{\sin(2\psi_{32}) \sin(2\psi_{21})} \]

\[ \Delta q_3 = - \frac{\Delta \beta_2}{\beta_2} \frac{1}{\beta_3} \frac{1}{\sin(2\psi_{32})} \]

See also AB seminar next week (R. Tomás)
RHIC Measurements

Proof of principle

- Kicked Data: Six quadrupole errors (Exp I)
- AC Dipole: Single quadrupole error (Exp II)
Exp I: Kicked ($\Delta \phi_{x,y}$, 6 Quads Trimmed)
Exp I: **Kicked** ($\Delta \phi$-beat, Recons Machine)

**Horizontal**

Reconstructed MADX
Meas

**Vertical**

Effect of 6 Trim Quads

$\delta(\Delta \phi) \times 10^{-2}$, Q Units

Longitudinal Position [km]
Exp I: Reconstructed Trims, ΔKL (Kicked)

- Machine Input
  Simplex (5000 Iters)

- R-Matrix (3 Iters)

Trims: \([\text{bi}8-\text{tq}4, \text{bo}7-\text{tq}5, \text{bo}11-\text{tq}4]\)
Trims: \([\text{bi}8-\text{tq}6, \text{bo}3-\text{tq}6, \text{bo}11-\text{tq}6]\)
Exp II: **AC Dipole**

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**Horizontal**

- **MAD-X**: Red circles
- **Baseline**: Blue dots
- **Quad Trimmed**: Black diamonds

**Vertical**

- **MAD-X**: Red circles
- **Baseline**: Blue dots
- **Quad Trimmed**: Black diamonds

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--- AC Dipole Data: Courtesy M. Bai
Exp II: AC Dipole ($\Delta \phi$-beat, Recons Machine)

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AC Dipole Data: Courtesy M. Bai
Exp II: AC Dipole (Reconstructed $\Delta KL$)

Quadrupole Trimmed: Q4IT8, 0.713 km
(Machine input verified by M. Bai)

R-Matrix (3 Iters)

$\Delta KL \ [1/m \times 10^{-3}]$

Longitudinal Position \ [km]
$\Delta \phi$ Measurement Err ($\sigma_\phi$)

Kicked & AC Dipole Exps
Ph. Err ($\sigma_\phi$), Low Chrom (Kicked & AC Dipole)

Kicked: $\sigma_\phi \approx 0.25$
AC Dipole: $\sigma_\phi \approx 0.15$
- $\sigma_\phi \sim 0.25^\circ$ for low chromaticity (baseline)
- $\sigma_\phi \gg 1.0^\circ$ with larger chromaticity, but not seen in SPS (need confirmation)
SPS Measurements
Transverse Impedance Localization

- HEADTAIL Simulations (proof of principle)
- Measurements in the SPS
Partial Impedance Story

E. Métral, BEAM’07:

- 2001: Cavities, pumping ports, MKE kickers removed (↓)
- 2003-06: +7 MKE kickers in LSS4 & LSS6 (↑, smaller than expected)
- 2007: -1 MKE kicker & sheilded 1 MKE kicker (↓, but not observed)

- $E_b = 26$ GeV, $\sigma_t = 0.5 - 0.6$ ns
- Some disagreement between predicted ↔ measured
- Also increase seen in $Z_{||}$ not observed in $Z_{\perp}$

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![Impedance Graph](image)

Many APC talks on impedance
Impedance Localization

Localization of the largest $Z_\perp$ sources using intensity dependent optics may help resolve some discrepancies.

Already tried in LEP & SPS:

- RF sections, IP2 & IP6
- 2800 shielded bellows
- Impedances concentrated in a few locations
- MKP, MKE kickers + some unidentified
Reactive impedance can be approximated as a defocusing quadrupole:

$$K_{eff} = \frac{eN_b}{2\sqrt{\pi}\sigma_z(E_b/e)}Im\{Z_\perp\}_{eff}$$

To 1st order, $\Delta K$ perturbation with intensity causes:

$$\Delta Q = \frac{1}{4\pi}\beta_k \Delta K$$

$$\frac{\Delta \beta(s)}{\beta(s)} = \frac{\beta_k \cos(2|\phi(s) - \phi_k| - 2\pi Q)}{2\sin(2\pi Q)} \Delta K$$

Procedure:

- Simulate/Measure phase advance between BPM pairs for varying intensities
- Appropriate noise cuts for BPM acceptance
- Linear fit: $\phi_I = \phi_0 + (\Delta \phi/\Delta N) N_b$
- $\Delta K = A^{-1}\{\Delta \phi/\Delta N_b, Q_x, Q_y\}$, where $A$ is model response matrix using
  - Quadrupoles (unconstrained/constrained)
  - Horizontal sextupole Bumps
HEADTAIL Example

Impedance Localization Simulations

- Track particles SPS lattice with multiple impedance sources
- Records turn-by-turn orbits at BPM locations
- Five intensities to compute slope and reconstruct $\Delta K$
  - Unconstrained
  - Constrained, defocusing in vertical plane

HT data courtesy: G. Rumolo, D. Quatraro
Multiple Imps, Flat Chamber

Fit: $6.5 \times 10^{-8} x + 0.13$

Fit: $-0.0013 x + 0.1797$
Reconstructed Sources

Vertical Ph. Adv

Flat Chamber, Multiple Impedances

Horizontal Ph Adv.

All Quads (x3)  
QDs Only (y2 axis)  
QDs Only
Intensity Fitted Slope $\{\Delta \phi_{a \rightarrow b}\}$

Fitted Slope (Ver)

Fitted Slope (Hor)

HT: Vertical
MADX: Recon

HT: Horizontal
MADX: Recon

Longitudinal Position [km]
Constrained Reconstruction (Iterative)

$$[R, \lambda I] \Delta \vec{K} = [\Delta \phi, 0]^T \{\Delta K_i < 0, \ QDs\}$$

- Fitted Slope (Ver)
- Flat Chamber, Multiple Impedances
- Defocusing Vertical Plane, ($\Delta K_i < 0, \ QDs$)

Kicker Locations

HT: Vertical
MADX: Recon

Constrained, 12 Iter
SPS Measurements
Impedance Localization Exps, Nov 2007

- MD1 Cycle, 26 GeV, $V_{RF} = 3$ MV, $\sigma_t = 0.55 \pm 0.05$ ns, $\xi_y \sim 1 - 3$ units
- Records turn-by-turn orbits at BPMs for $I_b = 5 - 140 \times 10^9$ p/bunch
- “Several” BPM filtering levels
- Reconstruct sources from intensity dependent optics
- Strong injection oscillations observed with high intensity
- RF voltage was set to 1.2 MV @100 ms, 3MV after 200 ms

Bunch Length Measurement

Bunch Length $\approx 2.2$ ns during experiment

$V_{RF} = 3$ MV, 200ms

Data Courtesy: T. Bohl, G. Papotti, B. Salvant
Tune Vs. Intensity (Nov 2, 2007)

QMeter BPM Tunes
(Single Precision BPM)

Hor: $Q_x$
Ver: $Q_y$
Fit: $0.0011x + 0.125$
Fit: $-0.017x + 0.2$

$\text{Im}(Z_T) \approx 18 \text{ M}\Omega/\text{m}$

SPS BPM Tunes
(Avg, Std from $\approx 100$ BPMs)

Hor: $Q_x$
Ver: $Q_y$
Fit: $0.0014x + 0.125$
Fit: $-0.0187x + 0.2$

$\text{Im}(Z_T) \approx 20 \text{ M}\Omega/\text{m}$
Orbit Shift Vs. Intensity

Systematic change in average and RMS orbit $\rightarrow \Delta Q_{x,y}$
Orbit gradient mainly localized in a couple of sectors, ($\Delta \phi_{s_2 \rightarrow s_1}$ ok)
BPM Data Selection for $\Delta \phi_{s2 \rightarrow s1}$

- Longer coherence observed at lower intensities ($\xi_{x,y}$ unchanged)
- Histogram of tunes from all BPMs ($\sim$100), all files ($\sim$410)
- Use Sussix to calculate frequency and phase within window
- Tune window & ph. adv of the (meas-model) used as selection criteria
Sample Ph. Adv [Q units]

Sample Fits (Nov 2, 2007)

Vertical Plane

Horizontal Plane

- Retain BPMs passing fit selection criteria
- Spread is larger in Vertical (Impedance, Chromaticity, ...
Fitted Slope $\Delta \phi / \Delta N$

- Similar slopes from 2 exps: Nov 2 (400 data sets) & July 27 (22 data sets)
- Vertical slope errors larger than horizontal (probably due to $\xi_y > \xi_x$)
Error Cuts (Nov 2007)

- Error in phase adv < 1deg (a bit high)
- Error in slope is 1 order of magnitude smaller than slope
Similar slopes for 2 exps: Nov 2 (400 data sets) & July 27 (22 data sets)

Relative error appears similar, not too much gain from statistics
Estimated $Z_\perp$ Distribution, I

- Few sources, but reconstruction sensitive to SVD cut (1.7 km spikes)
- Horizontal plane is inconclusive
Reconstruction not satisfactory, but main sources similar to unconstrained case.
Estimated $Z_\perp$ Distribution, III

$$[R, \bar{\lambda}I] \Delta \vec{K} = [\Delta \phi, 0]^T$$

\{constraint: $\Delta K_i < 0$, QDs $\rightarrow$ iterative weights\}
Estimated $Z_\perp$ Distribution, IV

- Phase beating induced by horizontal orbit bump, sextupole feed down
- Reconstruction useful for comparison, needs further investigation
Tune Vs. Intensity (RHIC)

Yellow: Au (Jan 23, 2008)

Blue: Protons (Mar 03, 2008)

- Observed tune shift negligible (need dedicated exps for confirmation)
- Need to separate $Q_x, Q_y$ to eliminate coupling effects
Conclusions

- **Powerful technique** to localize largest impedance locations
- Careful machine setup and data quality assessment is of primary importance
- Approx similar impedance distribution observed with different techniques
- Detailed analysis underway to infer **local impedance** contribution
- Future SPS experiments planned:
  - Baseline optics measurements with intensity scan
  - $\delta p/p \neq 0$ for **dispersion measurement** with intensity, additional constraint
  - Local orbit bumps at specific locations to infer/calibrate impedance contribution
- RHIC needs dedicated experiments to repeat impedance measurements

— Bon Appetit