Combined Effect of IBS and Impedance on the Longitudinal Beam Dynamics

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Electron-Ion Collider
Outlook

- NSLS-II main parameters
- NSLS-II Longitudinal Impedance Budget
- Diagnostic Methods
- Microwave Instability Threshold & Beam Pattern
- Combined Effect of IBS and Wakefield
NSLS-II Achieves Design Beam Current 500mA!

- We invested into creating diagnostic and monitoring devices since we had concern about the localized heating of the vacuum components, Bellows, RF Contact Spring, Septum Chamber, Stripline Kicker, Ceramics Chambers.

- IR thermal view cameras and temperature sensors available around the ring for temperature monitoring.

- Available diagnostic helped us in fixing problems and reaching 500 mA.

- The beam is stable at chromaticity +2/2 with Transverse Feedback System “ON”. A 10% gap for ion clearing.
## Main NSLS-II Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Energy $E_0 (GeV)$</td>
<td>3</td>
</tr>
<tr>
<td>Revolution period $T_0 (\mu s)$</td>
<td>2.6</td>
</tr>
<tr>
<td>Momentum compaction $\alpha$</td>
<td>$3.7 \times 10^{-4}$</td>
</tr>
<tr>
<td>RF voltage $V_{RF} (MV)$</td>
<td>3.4 (One RF system)</td>
</tr>
<tr>
<td>Synchrotron tune $\nu_s$</td>
<td>$9.2 \times 10^{-3}$</td>
</tr>
<tr>
<td>Energy loss $U (keV)$</td>
<td>BL: 287, 1DW: 400, 3DW: 674</td>
</tr>
<tr>
<td>Damping time $\tau_x, \tau_s (ms)$</td>
<td>BL: 54, 27, 1DW: 40, 20, 3DW: 23, 11.5</td>
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<tr>
<td>Energy spread $\sigma_\delta$</td>
<td>BL: $0.5 \times 10^{-3}$, 1DW: $0.71 \times 10^{-3}$, 3DW: $0.82 \times 10^{-3}$</td>
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<tr>
<td>Horizontal Emittance $\varepsilon_x (nm)$</td>
<td>BL: 2.1, 1DW: 1.4, 3DW: 0.9</td>
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<tr>
<td>Bunch length (at low current) $\sigma_z (mm)$</td>
<td>BL: 2.5, 1DW: 3.5, 3DW: 4</td>
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The longitudinal short-range wakepotential for each individual component (multiplied by the number of the components)
NSLS-II Total Longitudinal Wakefield

- Total longitudinal wakepotential of NSLS-II

- IR thermal image of the the flange joints

- RF spring in a special groove

- Details of the flange joint

- RW + GdfdL simulated geometric (gm) wakefields for a 0.3mm bunch length.

- Limitation on the single-bunch current result from ~740 RF contact springs design.

- Beam is stable at 500mA within M=1050 bunches (0.5mA/bunch)

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Electron Beam Diagnostic Methods

- In-Vacuum Undulator Radiation Spectrum
- Synchrotron Light Monitor Camera ($\eta_x = 0.13m$)
- Pinhole Camera (zero dispersion)
- Beam Spectra Spectra Measurements
  - BPM & Stripline Kickers - Network Analyzer
  - Infra-Red Optical Extraction Beamline (Large Aperture Dipole Chamber) - THz Schottky-diode detector

On axis UR spectrum measured at 7th harmonic of the IVU20 at the CHX NSLS-II beamline


Energy Spread Dependence on the Lattice

- The energy spread data estimated from IVU’s spectral measurements are shown for BL with purple dots, 3DW with magenta diamonds (SMI beamline) and 3DW with wine crosses (CHX beamline).
- The dependence of the microwave instability threshold on the energy spread according to the scaling law $I_{th1} \sim a \sigma_\delta^3$ is shown with the dashed grey line.
- The SLM camera data are presented for three different lattices, BL (green trace), 1DW (grey trace) and 3DW (blue trace) at $V_{RF} = 2.6 MV$. The energy spread is derived from the horizontal beam size measurements $\sigma_x(I_0)$.

$$\sigma_\delta(I_0) = \frac{1}{\eta_x} \sqrt{\frac{\sigma_x^2(I_0) - \epsilon_x(I_0) \beta_x}{\epsilon_x}}$$  
Eq. (1)

With $\sigma_x = 123 \mu m$, $\beta_x = 2.77 m$, $\eta_x = 0.13 m$ and $\epsilon_x = 0.9 nm$ for the 3DW - $\sigma_\delta = 0.087 %$
Microwave Fill-Pattern Measurements

- Beam spectra at $V_{RF} = 1.5\, MV$
- 3DW Lattice
- The local minima of the energy spread as a certain threshold current $I_{th}$ where two initially distinct frequencies merge, which we interpret as classical mode coupling as first described by Sacherer.
- However we were not able to observe, experimentally and numerically, the oscillating frequencies of the longitudinal modes before the beam becomes unstable.

Energy Spread and Bunch Length Dependence

- Energy spread ($\sigma_\delta$) growth below the microwave instability threshold ($I_{th}$) can be explained by the Intra-Beam Scattering (IBS) effect.
- Microwave beam pattern is due to the total longitudinal wakefield ($W_{||,tot}$).
- Bunch length measured by the streak camera.
- Tracking with $W_{||,tot}$ only shows $\sigma_\delta$ remains unchanged at $I_0 < I_{th}$.
- Energy spread and bunch length increase resulting from the IBS effect has been estimated by the ibsemittance code.
- IBS + Wakefield need to be simulated simultaneously!
Combined Effect of IBS & Wakefield

- The IBS effect results in increase the microwave instability threshold ($I_{th,\mu\text{W}}$).
- ELEGANT simulations with 160+ cores using the element-by-element NSLS-II lattice.
- Significant emittance growth vs. $I_0$.
- TMCI threshold is 0.7mA at chromaticity +2/+2.
- The same trend of $\varepsilon_y(I_0)$ growth with and w/o BBFS below the TMCI threshold.

**Measurements**

- $V_{RF} = 3\text{MV}$

**ELEGANT simulations of $\sigma_5(I_0)$ dependence**

- $V = 3\text{MV}$
- $I_0 = 8\text{pm}$
- $I_0 = 13\text{pm}$
- $I_0 = 13\text{pm}$ ELEGANT
- $I_0 = 21\text{pm}$
- $I_0 = 21\text{pm}$ TFB OFF
Vertical Emittance Growth

- If $\varepsilon_y$ - growth is a cause of the betatron coupling (zero vertical dispersion), then:

$$\frac{\varepsilon_y}{\varepsilon_{y0}} = \frac{\varepsilon_x}{\varepsilon_{x0}}$$


- $\varepsilon_y$ - growth at $I_0 < 1\, mA$ is due to the betatron coupling.
- $\varepsilon_y$ - growth at $I_0 > 1\, mA$ needs to be further investigated.
- Stabilizing effect of the Transverse Bunch-by-Bunch Feed Back System (BBFS) on the single bunch current. $I_0 > 6\, mA$ with BBFS “On”. Does it effect $\varepsilon_y$ at $I_0 > 1\, mA$?
- Adjusting the strength of the skew quadrupole to increase the vertical emittance w/o further lattice correction.
- The ratio is not holding for 2% and 3% (vertical dispersion?)
- Insufficient diagnostic resolution at low current.

![Normalized emittance graph](image)

- Experimental results of the normalized emittance for 1% coupling

- Unstable beam at $I_0 > 1.6\, mA$
Summary

• We have found and cross-checked changes in the electron beam energy spread at NSLS-II.

• Monotonic energy spread growth, below the microwave instability threshold, is due to the IBS effect.

• We benchmarked the ELEGANT code using the combined effect of IBS and $W_{||,tot}$ vs. the experimental data. Particle tracking simulations confirm the IBS effect on the microwave instability threshold.

• The IBS effect result in increase of $\sigma_s(I_0)$ and $\sigma_\delta(I_0)$.

• All diagnostic methods require the tune-up procedures to perform the precise measurements. Beam lines and the pinhole cameras need to be recalibrated before each beam study shift.
Acknowledgments

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