Impedance and Beam Dynamics Studies at Diamond Light Source

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Diamond Light Source

Acknowledgements
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Diamond Light Source

- Diamond is a 3rd generation 3 GeV light source in the UK
- In operation since 2007
- Produces very intense beams of X-rays, infrared and ultraviolet light
- ~500 staff

- 22 operational beam-lines
- 7 installed in optimization phase
- 6 under construction

2015-2016: 9000 users from both academia and industry
# Diamond parameters - nominal optics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (GeV)</td>
<td>3</td>
</tr>
<tr>
<td>Geom. emitt. x (nm.rad) (*)</td>
<td>2.66</td>
</tr>
<tr>
<td>Coupling (%)</td>
<td>0.3</td>
</tr>
<tr>
<td>Natural bunch length (mm) (*)</td>
<td>3.7</td>
</tr>
<tr>
<td>Momentum spread (*)</td>
<td>$1.07 \times 10^{-3}$</td>
</tr>
<tr>
<td>Circumference (m)</td>
<td>561.6</td>
</tr>
<tr>
<td>Mom. compaction factor</td>
<td>$1.6 \times 10^{-4}$</td>
</tr>
<tr>
<td>Tunes (x,y,s(*))</td>
<td>27.21/13.364/0.0042</td>
</tr>
<tr>
<td>Energy loss per turn (MeV) (*)</td>
<td>1.225</td>
</tr>
<tr>
<td>RF voltage (MV)</td>
<td>2.5</td>
</tr>
<tr>
<td>Average beta functions (x,y)(m)</td>
<td>10.65/12.84</td>
</tr>
</tbody>
</table>

(*) values with wigglers on
Ongoing activity on impedance and beam dynamics

- Single bunch
  - Nominal optics (E. Koukovini-Platia et al., IPAC16, MOPOR018)
  - Low alpha optics (T. Chanwattana et al., IPAC16, TUPOR012)
  - Effect of the transverse feedback with various chromaticities

- Multi-bunch (R. Bartolini et al., IPAC16, TUPOR013)

- Double Double Bend Achromat (DDBA) cell (installation shutdown planned for October 2016)
  - Impedance calculation with CST
Macro-particle simulation with sbtrack

- Measured single bunch instabilities are analysed using sbtrack
- Multi-particle 6-dimensional tracking code
- Originally written in C (R. Nagaoka)
- Matlab version available (J. Rowland)
- Collaboration between Diamond and SOLEIL on sbtrack/mbtrack codes
- Recent modification: arbitrary number of resonators
Impedance model

• Diamond has a stainless steel vacuum chamber (2 mm thickness)
• Average half-apertures: width=40 mm, height=12 mm (or 13mm for open ID’s)
• In-vacuum devices (copper coated) close down to 5 mm

Analytic calculation of resistive wall impedance (RW) for elliptical chamber

• The geometric impedance of the ring is approximated by a single broad-band resonator, characterized by Q, R and $\omega_r$

Broad-band resonator impedance (BBR)

• A purely inductive impedance had to be included in the longitudinal model to reproduce the measured bunch length
Bunch lengthening measurements

- The bunch profile is measured using a streak camera ($V_{RF}=2.5$ MV)
- Longitudinal BBR parameters: $Q=1$, $f=8.3$ GHz, $R_s=0.5$ kΩ
- Inductance of 70 nH
- RW

Longitudinal impedance model

Next step take energy spread measurements and match with model

Calibration= 0.1617ps/pixel

Courtesy L. Bobb
Horizontal plane \((Q'x=0, Q'y=3), V_{RF}=2.5\) MV

**Measurements**

- Excite the beam using the stripline kicker, part of the Transverse Multi-Bunch Feedback system (TMBF)

**Simulation**

- sbtrack: multi-particle 6-dimensional tracking code
- Model: RW, BBR \((Q=1, f=8.3\) GHz, \(R_x=5\) kΩ/m )
**Vertical plane (Q’x=3, Q’y=2), V_{RF}=2.5 MV**

### Measurements

- Threshold at \( (0.6\pm0.05) \) mA

### Simulation

- Model: RW, BBR \((Q=1, f=8.3 \text{ GHz}, R_y = 0.10 \text{ M}\Omega/m )\)

\[
\text{Im}(Z_{\text{eff}}) = (334.2\pm0.5) \text{ k}\Omega/m
\]
Normalized tune shift with Sussix on data

Sussix applied on TMBF data
Mode coupling between $m=0$ and $m=-1$ (data)
Vertical plane ($Q'y=0$, $Q'x=3$)

Open Insertion Devices
(13 mm half aperture)

- Measured $\sim 0.74$ mA
- $sbtrack \sim 0.7$ mA

Different voltage 1.7 MV

- Measured $\sim 0.51$ mA
- $sbtrack \sim 0.55-0.6$ mA

The effect of the IDs can be sufficiently explained by the resistive wall impedance.
Low alpha optics

- Diamond is regularly operated in low-alpha mode to provide THz coherent synchrotron radiation (CSR) and short X-ray pulses to users.
- An ultra-low alpha mode has been considered to shorten the bunch length even further.

\[ \sigma_0 = \frac{c\sigma_E}{f_{rev}} \sqrt{\frac{|\alpha_c|E_0}{2\pi\hbar e V_{RF} \cos \phi_s}} \]

- A reduction in the bunch length extends the wavelength range in which the bunch emits coherently towards the THz/far infrared region.
- Minimize alpha -> linear optics needs to be tuned such that the integrated dispersion inside the bending magnets is close to zero.
- Measurements recorded using a Fourier Transform Infrared (FTIR) interferometer on the MIRIAM beam-line at Diamond are compared with sbtrack results.
Ultra low alpha optics

Measured data
\( \alpha_c = -2 \times 10^{-6}, \)
\( V_{RF} = 3.4 \text{ MV}, \)
800 bunches

CSR bursting threshold
~8 \( \mu \text{A} \)

sbtrack

BBR1: \( R = 0.5 \text{ k}\Omega, f = 8.3 \text{ GHz}, Q = 1 \)

BBR2: \( R = 90 \text{ k}\Omega, f = 100 \text{ GHz}, Q = 1 \)

RW

CSR with shielding

T. Chanwattana
Ultra low alpha optics

\[ \alpha = -2 \times 10^{-6} \]

<table>
<thead>
<tr>
<th>theory</th>
<th>simulation</th>
<th>measurement</th>
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</table>

Work in progress
T. Chanwattana

FTIR spectra for \( \alpha = -2 \times 10^{-6} \)

Measured

sbtrack
Effect of feedback on single bunch instabilities

• Single bunch measurements with and w/o the Transverse Multi Bunch Feedback (TMBF)
• Record turn by turn (tbt) data and tune shifts
• Vary vertical chromaticity from -2.5 up to 2.5 and increase the bunch current till the instability onset

• Machine settings
  – Single bunch, 2.5 MV, wiggler on, closed ID’s at minimum gap of 5 mm, coupling 0.23%
  – Set Q’x=3 and correct Q’y as required
1. For negative chromaticity we gain a factor of 10 in current
We can store much higher current in our normal operation with chromaticity of 2
2. No effect on the TMCI is observed
3. Increase of current by a factor of 2-4 for $\text{Q'\gamma} > 0$
Effect of the feedback gain

Effect of feedback gain

- no feedback
- feedback on (0dB)
- feedback on (-6dB)
- feedback on (-12dB)

Threshold [mA]

Vertical chromaticity
We could reproduce very well all threshold onsets without the feedback (blue and cyan). Performance of the TMBF was different. Phase of feedback was 180°. Perhaps there was a phase difference between the RF and TMBF? Shutdown 1 and run 18

Action
1. Repeat measurements to understand the reduction in performance of the TMBF
2. Study the effect of the feedback phase on the TMCI threshold
Analysis of tbt data, 0 chromaticity

No feedback

**TMCI threshold: 0.59 - 0.6 mA**

0 dB

**TMCI threshold: 0.56 - 0.57 mA**
HDTL regime, 2.5 chromaticity
\(m > 0\) get unstable

\[\text{No feedback} \quad \text{Threshold: 1.89 mA}\]

\[\text{0 dB} \quad \text{Threshold: 2.6 mA}\]
HDTL regime, -2.5 chromaticity
m=0 gets unstable

---

No feedback
Threshold: ~ 0.032 mA

Can store 11 times higher current with 0 dB feedback gain

0 dB feedback gain
Threshold: 0.36-0.37 mA
Control of TMCI with feedback

- Paper from J. Byrd in ALS
- Had to adjust empirically the feedback phase to be purely resistive to maximize the damping rate.
- TMCI threshold from 20 mA to 27 mA, with FB operating as purely resistive.
- 20 mA to 37 mA with a 26 dB gain pre-amplifier inserted before the high power amplifier.

![Graph showing measured transverse damping rates for various gain settings]

- Reconfigured existing multibunch transverse FB system to work for high current single bunch.
- FB has arbitrary phase adjustment using 2 PUs about 60 degrees apart in betatron phase.
- Sensitive buttons and electronics allow for high gain.
- Both vertical and horizontal FB used to control TMCI.

J. Byrd
TMC (fast head-tail) instability
Feedback applicability – history

Theory (2-particle model, Vlasov equation, mode coupling):

- S. Myers, LEP Note 436, 1983
- V. Danilov, E. Perevedentsev, CERN SL/93 - 38 (AP), 1993
- G. Sabbi, CERN SL - 96 - 02 (AP), 1996

TMC instability can be suppressed by a reactive feedback.
Resistive feedback is not effective.

Experiments:

- D. Brandt, Proc. of 5-th Workshop on LEP Perform
- S. Myers, Proc. of PAC-1987
- M. Karliner, V. Kiselev, A. Medvedko, V. Smaluk, A. Zelenin, N. Zinevich, EPAC-1996
- LEP experience: reactive feedback provided 5% increase of beam current.
- VEPP-4M experience: resistive feedback is more effective than reactive one (contradiction with the theory).

A. Burov: Extreme simplicity of 2-particle model, with NHT this contradiction disappears.
Resistive damper cannot increase the TMCI (LHC impedance model) and variation of the phase does not help much. Reactive fb should be used for 0 chromaticity in that case.
Simulation codes

Collaboration with CERN

• Interest to benchmark sbtrack with PyHEADTAIL and DELPHI
  – Nominal optics
  – Low alpha optics (CSR with shielding is needed)
• Use those codes to simulate the effect of the transverse feedback
Grow damp experiment at Diamond

- 936 bunches, 2 ns (500 MHz) spacing (full fill: M=936)
- 530 kHz revolution frequency, current up to 300 mA
- bunch length 15-25 ps rms – with current

- Artificially excite mode $\mu$ by using a stripline kicker for 250 turns at the frequency $(pM + \mu)\omega_0 + \omega_\beta$

- Stop the excitation and measure free oscillations for 250 turns

- Run feedback to damp any unstable mode or any residual oscillation for 250 turns

- Repeat for all modes
Grow damp experiment at Diamond

Example of mode that is naturally damped
Recording the complex amplitude and phase on a turn-by-turn basis only of the mode previously excited. Data reduced from 1.3 GB to 5.6 MB.

Repeat for all modes \( \mu = 0, 1, \ldots, M - 1 \)

Offline post processing gives the frequency shift and damping or growth rate (take away radiation damping and chromatic damping (if any))
Growth rates of vertical coupled bunch modes

**Vertical TMF data**
- full fill - zero chromaticity - ID gap open

Data suggest resistive wall and few high Q resonators

\[
\Delta \Omega_n = -\frac{i}{4\pi} \frac{\omega_0 \beta}{E/e} I \sum_{p=-\infty}^{\infty} Z_\perp(\omega_{pn}) h(\omega_{pn})
\]

\[
\omega_{pn} = (pN_b + n + \nu_\beta)\omega_0 \quad h(\omega) = e^{-\omega^2 \sigma^2}
\]

\[
Z_\perp = Z_\perp^{rw} + \sum Z_\perp^{res}
\]

**Resistive Wall**
\[\beta = 12.25 \text{ m}, \quad b = 13.5 \text{ mm}, \quad \rho = 7.3 \times 10^{-7} \Omega \cdot \text{m}\]

\[
\frac{Z_{x,y}^{rw}}{L} = G_{1x,y} \frac{\text{sgn } \omega + i}{\pi b^3} \sqrt{\frac{Z_0 c \rho}{2}} |\omega|^{-1/2}
\]

**Resonator**
\[
Z_\perp^{res} = \frac{R_s}{\frac{\omega}{\omega_r} + iQ \left(\frac{\omega^2}{\omega_r^2} - 1\right)}
\]

Courtesy V. Smalyuk, R. Bartolini
Resonance 1
\[ f_r = (19N_b - 22)f_0 = 9.4817 \text{ GHz} \]
\[ R_s = 2.8 \text{ M}\Omega/m \quad Q = 2000 \]

Resonance 2
\[ f_r = (18N_b - 64)f_0 = 8.9595 \text{ GHz} \]
\[ R_s = 1.4 \text{ M}\Omega/m \quad Q = 20000 \]

Resonance 3
\[ f_r = (13N_b + 119)f_0 = 6.5590 \text{ GHz} \]
\[ R_s = 0.8 \text{ M}\Omega/m \quad Q = 1000 \]

Resonance 1 – mode -22
\[ f_r = 9.4200 \text{ GHz}; \quad Q = 2000; \quad \Delta f = 61.7 \text{ MHz} \]

Resonance 2 – mode -64
\[ f_r = 8.9081 \text{ GHz}; \quad Q = 20000; \quad \Delta f = 51.4 \text{ MHz} \]

Resonance 3 – mode 119
\[ f_r = 6.7578 \text{ GHz}; \quad Q = 1000; \quad \Delta f = 198.8 \text{ MHz} \]
Effect of closing the IDs

Closing the gap of all IDs changes the geometric and RW impedance

Forest of spikes at modes 100-140 has been associated to IDs
Repeat measurements

- Large resonant peak moved in the last months from $\mu = 21$ at $\mu = 81$
- Same conditions: full fill 936 bunches – 0 chromaticity – IDs open
- Collimator blades do not correctly return to set position when moved away and back again (using collimator to dump low current beam in MD had resulted in large drift during the last run)

Collimator blade at 3.5 mm

Collimator blade at 2.5 mm

*Courtesy R. Fielder*
Further machine studies revealed that the vertical collimator is responsible for the large peak in the vertical impedance (scan full gap from 10 mm to 5.5 mm. Nominal position at 7 mm)

*The peak of V impedance scans ~300 modes i.e. ~150 MHz*
Further modelling of collimator (I)

The failure to predict this large impedance contributor triggered a new analysis in trying to understand what features of the collimator are responsible and what level of detail should be included in the model.

R. Fielder
Further modelling of collimator (II)

Vertical impedance of symmetric (top-bottom) structure
tiny shift frequency with gap

The shift in frequency with gap moves the opposite way than in the measurements, and also CST predicts an amplitude reduction which is not experimentally observed (work in progress)
Double Double Bend Achromat (DDBA)

- 1 DDBA cell is going to be installed and commissioned in October 2016
- Many horizontal aperture changes
- Dipole vessels, transitions, ID, bellows etc
- Impedance studies of the DDBA components
DDBA components

- ID full structure
- ID transition taper
- Dipole radiation shading bumps
- Pumping ports
- Upstream/downstream tapers
- U/s transition
- Dipole vessel
Dipole Vessel

- Beam pipe
- x-rays leg
Just by importing the dipole vessel in CST, the beam path follows the x-rays path rather than its own.
Rotating the geometry around the beam path

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sigma</td>
<td>3.3 mm</td>
</tr>
<tr>
<td>Max. beam frequency (-20 dB)</td>
<td>31.0277 GHz</td>
</tr>
<tr>
<td>Beta</td>
<td>1</td>
</tr>
<tr>
<td>Charge</td>
<td>1e-009 C</td>
</tr>
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</table>
The path of the beam is now straight. The x-rays path is bent.
Vacuum and copper as surrounding material. Background PEC, direct integration.
**Summary**

**Single bunch**
- As a first approximation, an impedance model consisting of a BBR and RW impedance is found to match well the transverse measured tune shift and thresholds for nominal optics. To match the measured bunch lengthening an inductive impedance was necessary
  - Cases of $\xi=0$, $\xi>0$, different RF voltages, closed and open ID’s
- A model on low alpha optics is also developed to match the measured bunch length and emitted spectrum

**Multi bunch**
- The TMBF allowed extensive and repetitive grow damp measurements $\rightarrow$ regular monitoring of the machine impedance
- Work ongoing to identify all impedance contributions

**Collaboration with CERN**
- DDBA studies with CST
- Benchmark of sbtrack with PyHEADTAIL and DELPHI in the direction of simulation with feedback
Thank you!