Beam dynamics studies with a 3rd harmonic cavity for the ESRF EBS

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• Touschek lifetime for ESRF Extremely Brilliant Source (EBS)
• bunch lengthening with 3\textsuperscript{rd} harmonic cavity
• bunch lengthening with impedance and 3\textsuperscript{rd} harmonic cavity
• optimum voltage of harmonic cavity
• effect of 3\textsuperscript{rd} harmonic cavity on dynamic aperture
The most critical modes for the Touschek lifetime are the ones with high current per bunch (4B and 16B).

<table>
<thead>
<tr>
<th>filling mode</th>
<th>$I_{\text{tot}}$ (mA)</th>
<th>number of bunches</th>
<th>$I_b$ (mA)</th>
<th>$\varepsilon_y$ (pm)</th>
<th>delivery time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-bunch</td>
<td>200</td>
<td>868</td>
<td>0.23</td>
<td>5</td>
<td>~70%</td>
</tr>
<tr>
<td>16 bunches</td>
<td>90</td>
<td>16</td>
<td>5.6</td>
<td>5</td>
<td>~25%</td>
</tr>
<tr>
<td>4 bunches</td>
<td>40</td>
<td>4</td>
<td>10</td>
<td>5</td>
<td>~5%</td>
</tr>
</tbody>
</table>
Without harmonic cavity, with impedance of 0.35 $\Omega$, the Touschek lifetime for the three modes are:

- MB: 20 h
- 16B: 1.9 h
- 4B: 1.3 h

A possible upgrade of the ESRF EBS will be the installation of a third harmonic cavity to increase LT in few bunch mode.
The superconductive harmonic cavity will be passive and almost exactly in phase with the beam. We can simulate it with the Accelerator Toolbox (AT). A small detuning with the beam is used to control the voltage of the cavity.

With 6.5 MV, the HC voltage is 1.98 MV
Tracking is done with radiation damping and quantum fluctuation, for 24000 turns and \( \sim 10^5 \) particles, using AT.

The equilibrium distribution is not gaussian and not symmetric, due to the not optimal phase of the HC.

The phase of the HC is set at each turn to the bunch phase.
TOUSCHEK EFFECTIVE BUNCH LENGTH (TEBL)

We need to compute the effective bunch length for the Touschek lifetime when the bunch is not gaussian, assuming no correlation between longitudinal and transverse distribution.

In Piwinski formula:

\[ \frac{1}{\tau} \propto \int \rho^2(x,y,z) dx dy dz \]

For a gaussian beam:

\[ \int g(z) \, dz = 1 \]

\[ g(z) = \frac{1}{\sqrt{2\pi}\sigma_z} e^{-\frac{z^2}{2\sigma_z^2}} \]

\[ \frac{1}{\tau} \propto \frac{1}{8\pi^3 \sigma_x \sigma_y \sigma_z} \]

If \( g(z) \) is an arbitrary \( f(z) \):

\[ \frac{1}{2\sqrt{\pi}\sigma_z} \Rightarrow \int f^2(z) \, dz \]

\[ \sigma^{TE}_{z} = \frac{1}{2\sqrt{\pi} \int f^2(z) \, dz} \]

Courtesy of B. Nash
The bunch length with impedance of ESRF-EBS is always shorter than in the present machine, due to smaller impedance and shorter zero-current bunch length.
We want to simulate the bunch lengthening with both the effect of impedance and the effect of the harmonic cavity.

S. White has implemented an inductive impedance element for the Accelerator Toolbox, which agrees with Haissinski equation.
3rd Harmonic Cavity and 0.35 Ω Impedance

- 0 current: $\sigma_{HC}=5.3 \sigma_{noHC}$
- MB current: $\sigma_{HC}=4.1 \sigma_{noHC}$
- 16B current: $\sigma_{HC}=2.5 \sigma_{noHC}$
- 4B current: $\sigma_{HC}=2.3 \sigma_{noHC}$
The gain in Touschek effective bunch length with the harmonic cavity is smaller if there is also bunch lengthening due to impedance.
The nominal voltage for 6.5 MV in the main cavities is 1.98 MV.
LONGITUDINAL BUNCH DISTRIBUTION WITH DIFFERENT HC VOLTAGE
16B CURRENT

without HC
TEBL=9.9mm

HC with nominal voltage (1.98MV)
TEBL=24.1mm

HC with 92% of nominal voltage
TEBL=17.5mm

HC with 108% of nominal voltage
TEBL=29.1mm
On-energy dynamic aperture is substantially smaller if the RF cavity is on. Particles with large amplitude have a longer trajectory and arrive later to the cavity, so they change their energy.

The effect can be reduced changing the chromaticity: high chromaticity is beneficial to reduce the path lengthening with amplitude in ESRF EBS lattice.
ΔE without HC

ΔE with HC

path length change
EFFECT OF THE HARMONIC CAVITY ON THE DYNAMIC APERTURE

<table>
<thead>
<tr>
<th>D.A.</th>
<th>Injection efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(120,5) nm</td>
</tr>
<tr>
<td>Nominal</td>
<td>-8.2 +/- 0.4</td>
</tr>
<tr>
<td>+ Harmonic Cavity</td>
<td>-8.7 +/- 0.6</td>
</tr>
</tbody>
</table>

Harmonic cavity 3\(^{rd}\) order

Courtesy of S. Liuzzo
CONCLUSION

• Touschek lifetime for ESRF EBS can be increased with a harmonic cavity, that increases the Touschek effective bunch length, by a factor
  - 2.3 for 4B mode
  - 2.5 for 16B mode
  - 4.1 for MB mode

• the gain could be larger if we accept a doubled peak bunch

• the harmonic cavity increases the on-energy dynamic aperture and the injection efficiency
MANY THANKS FOR YOUR ATTENTION