$\beta^*$ determination in van der Meer optics

– LHC Lumi Days –

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Introduction and Motivation

Goal
Establish a value for $\beta^*$ that fits preferences from experiments while keeping the measurement reliable and accurate enough.

Methodology

- Analysis of the measurements carried out during the MD on vdM optics.
- Simulations using MADX to extend the study to different optics.
**\( \beta^* \)** measurement using k-mod

Modulation of the strength of the last quadrupoles (usually Q1) the IP induce a change in tune that allows to determine the \( \beta \)-function at the quadrupole\(^1\).

The \( \beta \) at the quadrupole is given by:

\[
\beta_{av} \approx \pm 4\pi \frac{\Delta Q}{\Delta kL} \tag{1}
\]

The value for \( \beta^* \) is calculated from the value of \( \beta \) at the quadrupole:

\[
\beta^*_{quad} \rightarrow (\beta_w, w) \rightarrow \beta^* \tag{2}
\]

\(^1\)F. Carlier, R. Tomas, Accuracy and feasibility of the \( \beta^* \) measurement for LHC and High Luminosity LHC using k-modulation, PRAB 20, 011005.
K-mod technique limitation in vdM$^2$

- The uncertainty on $\beta^*$ is closely related to uncertainty in $\beta$ at the nearest quadrupole.

\[
\frac{\sigma_{\beta^*}}{\beta^*} = \frac{\beta^* + \frac{L^2}{\beta^*}}{|\beta^* - \frac{L^2}{\beta^*}|} \frac{\sigma_\beta}{\beta} = \Lambda \frac{\sigma_\beta}{\beta}
\]

- Due to optics properties, when $\beta^* \approx L^*$ (case of vdM optics), a small error in $\beta$ may drive a huge error in $\beta^*$.

- One should avoid $\beta^* \approx L^*$.

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$^2$L. van Riesen-Haupt, K-modulation developments via simultaneous beam based alignment in the LHC, Proceeding IPAC17
**β** measurement limitations

Uncertainties in observables have a significant impact on the reconstructed value of **β**.

**Uncertainties**
- Tune jitter
- **β**-beating
- Orbit shift/jitter
- Misalignment
- Quadrupole strength
- Coupling
- ...

**Table:** Tune uncertainties during the MD devoted to vdM optics measurements

<table>
<thead>
<tr>
<th></th>
<th>B1</th>
<th>B2</th>
</tr>
</thead>
<tbody>
<tr>
<td>δQₓ[10⁻⁵]</td>
<td>3.2</td>
<td>2.3</td>
</tr>
<tr>
<td>δQᵧ[10⁻⁵]</td>
<td>3.2</td>
<td>3.4</td>
</tr>
</tbody>
</table>
One quadrupole modulation per IP (IP1/IP5/IP8) per side (L/R).
Two modulations in IP8 with and without orbit feedback.
2016 MD on vdM: $\beta^*$ measurement

Uncertainties

- Magnet misalignment of 6 mm rms.
- Magnet strength error: $\Delta K/K = 10^{-3}$.
- Tune uncertainty: $\delta Q = 5.0 \cdot 10^{-5}$.

<table>
<thead>
<tr>
<th></th>
<th>Beam 1</th>
<th></th>
<th>Beam 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>IP</td>
<td>$\beta^*_x$</td>
<td>$\beta^*_y$</td>
<td>$\beta^*_x$</td>
</tr>
<tr>
<td>IP1</td>
<td>17.4 ± 0.02</td>
<td>18.11 ± 0.02</td>
<td>17.73 ± 0.02</td>
</tr>
<tr>
<td>IP5</td>
<td>33.06 ± 24.17</td>
<td>18.00 ± 3.7</td>
<td>16.21 ± 0.02</td>
</tr>
<tr>
<td>IP8</td>
<td>21.52 ± 0.03</td>
<td>19.97 ± 0.03</td>
<td>26.35 ± 2</td>
</tr>
</tbody>
</table>

- Reasonable for IP1.
- Very bad measurement for $\beta^*_x$ in IP5 and $\beta^*_y$ in IP8.
Can we explain the results? $\beta$-beating (B1)
Can we explain the results? $\beta$-beating (B2)
Can we explain the results? $\beta$-beating in IRs

Table: $\beta$-beating at the location of the BPM of the last quadrupoles on both sides of the IP.

<table>
<thead>
<tr>
<th>IP</th>
<th>$\Delta \beta_x / \beta_x [%]$</th>
<th>$\Delta \beta_y / \beta_y [%]$</th>
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</tr>
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<tr>
<td></td>
<td>Beam 1</td>
<td>Beam 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>R</td>
<td>L</td>
<td>R</td>
</tr>
<tr>
<td>IP1</td>
<td>6.3</td>
<td>5.8</td>
<td>1.0</td>
<td>0.1</td>
</tr>
<tr>
<td>IP5</td>
<td>6.8</td>
<td>13</td>
<td>9.4</td>
<td>8.5</td>
</tr>
<tr>
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<td>8.6</td>
<td>7.7</td>
<td>1.3</td>
<td>0.5</td>
</tr>
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Beam 1:
- $\Delta \beta_x / \beta_x [%]$:
  - IP1: L = 6.3, R = 5.8
  - IP5: L = 6.8, R = 13
  - IP8: L = 8.6, R = 7.7

Beam 2:
- $\Delta \beta_y / \beta_y [%]$:
  - IP1: L = 1.0, R = 0.1
  - IP5: L = 9.4, R = 8.5
  - IP8: L = 1.3, R = 0.5
Can we explain the results? $\beta$-beating

- Although global $\beta$-beating is reasonable, local $\beta$-beating at the last quadrupole may have a significant impact on $\beta^*$.  
- Up to 10% $\beta_x$-beating in MQXA.1R5.B1. This could explain the bad result of $\beta^*_x$ in IP5.  
- In general, larger $\beta$-beating induces larger errors in $\beta^*$. 

![Graph showing $\beta_x^*$ and $\beta_y^*$ vs. $<\Delta\beta/\beta>$ in %]
Can we explain the results? Waist influence

- Large waists lead to large errors in $\beta^*$.
- B1H in IP5 has a large waist.
- But small waist does not ensure good measurements.
- It may help to try to correct both $\beta$ and waist beating.
K-mod simulations

▶ Evaluate the impact of uncertainties in a wide range of optics possibilities.

▶ 10 different optics configurations have been tested $\beta^*(IP1/IP5) \approx (12, 14, 16, 19, 22, 25, 30, 33, 40, 50) \text{ m}$.

▶ Crossing angle ($\theta/2 = 50 \mu\text{rad}$) effect is negligible.

▶ Uncertainties in $Q$, $K$ and misalignments.

▶ Ideal machine for the rest.

▶ As in measurements, modulations are simulated varying the tune by $\Delta Q \sim \pm 0.01$. 

![Graph showing modulation versus tune change for different values of $\beta^*$ and crossing angle.]
Simulations: $\Delta \beta^*/\beta^*$ vs $\delta Q$ (IP1)

- Increase of uncertainty in $\beta^*$ with tune uncertainty.
- As seen previously, for $\beta^* \approx L^*$, the error in $\beta^*$ diverges.
- Current expected tune uncertainty: $3.0 - 5.0 \cdot 10^{-5}$.
- For HL-LHC, it is required a smaller tune uncertainty ($\sim 2.5 \cdot 10^{-5}$).
Simulations: $\Delta \beta^*/\beta^*$ vs. $\beta^*$

- Close to ideal case.
- Final value on $\Delta \beta^*/\beta^*$ will be affected by many factors not considered here.
- Error for $\beta^* < L^*$ decreases faster than for $\beta^* > L^*$.
- $\beta^*$ uncertainty below $0.5\%$ for $\beta^* < 19$ m.
Conclusions

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- The smaller $\beta^*$ the better (from the machine perspective).

Safety margin accounting for $\beta^*$-eating.

- Exlude region: $\beta^* = \beta_\infty \pm 20\%$.

- $\beta^* \leq 17$ m seems to be a reasonable choice.

- Uncertainty below $0.5\%$ for near to ideal case.

- Larger $\beta^*$ is also possible (40 m?) but not for HL.

- Further analysis required to better estimate $\beta^*$ uncertainty.

- MC-like simulations including $\beta$-eating and waist eating.

- The uncertainty on $\beta^*$ might be further reduced if some time is devoted to vdM optics correction (i.e. reduce waist, $\beta$-eating...).

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Back up
Simulations: $\Delta \beta^*/\beta^*$ vs $\delta Q$ (IP5)

▶ Same behaviour as that of IP1.
Can we explain the results? Phase influence

- Analyzed phase phase advance between Q1 left and right via AC-dipole and and compared to reconstructed from kmod.
- Expected phase advance \( \sim 45 \text{ degrees} \).
- Fully confirms that the \( \beta_x^* \) measurement in IP5 is bad.
- Errors in phase beyond 10\% make measurement less reliable.