Update on the development of the fast harmonic kicker with new beam parameters

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1. Beam dynamics simulation using the ELEGANT
The ELEGANT simulation setup

- To demonstrate longitudinal dynamics through the kickers with new parameters.
- Bunch charge was reduced to 0.02 pC.
- Longitudinal beam distribution is Gaussian with 30mm (rms).
- Beam size is set to be as small as 0.31mm (rms)
- The spatial profile of the harmonic kicker is modeled as a delta-function.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Prev.</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>55 MeV</td>
<td>55 MeV</td>
</tr>
<tr>
<td>Kick angle</td>
<td>1 mrad</td>
<td>2.5 mrad</td>
</tr>
<tr>
<td>( f_b )</td>
<td>476.3 MHz</td>
<td>476.3 MHz</td>
</tr>
<tr>
<td>( Q_b )</td>
<td>3.2 nC</td>
<td>2 nC</td>
</tr>
<tr>
<td>Turns</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>( f_{kick} )</td>
<td>47.6 MHz</td>
<td>86.6 MHz</td>
</tr>
<tr>
<td>Energy spread</td>
<td>3E-04</td>
<td>3E-04</td>
</tr>
<tr>
<td>Bunch length</td>
<td>30 mm</td>
<td>20 mm</td>
</tr>
<tr>
<td>( \alpha_x=\alpha_y )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( \beta_x=\beta_y )</td>
<td>10 m</td>
<td>10 m</td>
</tr>
<tr>
<td>( \varepsilon^{n_x}=\varepsilon^{n_y} )</td>
<td>1.074 ( \mu ) m</td>
<td>1.074 ( \mu ) m</td>
</tr>
<tr>
<td>Beam distr.</td>
<td>Gaussian</td>
<td>Beer can</td>
</tr>
</tbody>
</table>

Simulation setup

Transfer Matrix 1

Transfer Matrix 2

With \( \pi \)-phase advance

out-kicker in-kicker

Pre-kicker Post-kicker

Cooler

Beam parameters
Harmonic kick to the bunches

- The kick consists of 5 (odd) harmonic modes with base frequency of 86.6 MHz (in one cavity).
- The kick is vertically downward and generates 137.5 kV for 2.5 mrad deflection.
- The bunches in-between the kicks are not affected by residual kicks (by adjusting DC).
- The kicked bunches are flat (with no angular spread).
- The equal amplitude for all the harmonics were used.

![The temporal profile of the kick](image)

<table>
<thead>
<tr>
<th>Mode</th>
<th>freq.</th>
<th>Amp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>86.6 MHz</td>
<td>25 kV</td>
</tr>
<tr>
<td>2</td>
<td>259.8 MHz</td>
<td>25 kV</td>
</tr>
<tr>
<td>3</td>
<td>433 MHz</td>
<td>25 kV</td>
</tr>
<tr>
<td>4</td>
<td>606.2 MHz</td>
<td>25 kV</td>
</tr>
<tr>
<td>5</td>
<td>779.4 MHz</td>
<td>25 kV</td>
</tr>
<tr>
<td>DC</td>
<td></td>
<td>12.5 kV</td>
</tr>
</tbody>
</table>
Pre-(Post-) kicker implementation

Expanded view of the kick profile

Defines amplitude of the pre-kick: 0.277

\[ \pm 6\sigma \]

Modes

<table>
<thead>
<tr>
<th>Modes</th>
<th>freq.</th>
<th>Amp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>86.6 MHz</td>
<td>25 kV</td>
</tr>
<tr>
<td>2</td>
<td>259.8 MHz</td>
<td>25 kV</td>
</tr>
<tr>
<td>3</td>
<td>433 MHz</td>
<td>25 kV</td>
</tr>
<tr>
<td>4</td>
<td>606.2 MHz</td>
<td>25 kV</td>
</tr>
<tr>
<td>5</td>
<td>779.4 MHz</td>
<td>25 kV</td>
</tr>
<tr>
<td>DC</td>
<td>-</td>
<td>12.5 kV</td>
</tr>
<tr>
<td>pre</td>
<td>952.6 MHz</td>
<td>-38.1 kV</td>
</tr>
</tbody>
</table>
Longitudinal profiles of angular divergence

At the entrance of cooling channel

With pre-kicker

After out-kick with pre-kicker

3

8
Angular divergence of the kicked bunch

Initial distribution

After the first in-kick

Transverse profile

Initial distribution

After the first in-kick

Phase space profile

Initial distribution

After the first in-kick

After 11 turn

After 11 turn
Emittance growth

Emittance growth with the pre-/post-kicker

At the entrance of cooling channel

At the entrance of cooling channel
2. Beam dynamics simulation using the GPT
Beam dynamics simulation with GPT

- The effect of the kick on the magnetized beam circulating the ring is checked.

- Magnetized round beam is studied.
- More realistic beam size of 1.8 mm \((rms)\) is used.
- Space charge effect is taken into account with 2nC.
- The kicks are now modeled to have a spatial Gaussian profile, which is fitted from CST simulation.

Benchmark with the ELEGANT simulation
- With a realistic beam, space charge effect is studied.
- With a realistic beam, magnetization is studied (without space charge effect).
- With a realistic beam, combined effect of magnetization and space charge is studied.

The parameters for GPT simulation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam distr.</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Beam energy</td>
<td>55 MeV</td>
</tr>
<tr>
<td>(\sigma_x = \sigma_y)</td>
<td>1.8 mm</td>
</tr>
<tr>
<td>(\varepsilon_{nx} = \varepsilon_{ny})</td>
<td>36 mm-mrad</td>
</tr>
</tbody>
</table>

\[
m\gamma \sigma^2 \dot{\phi} + \frac{e \sigma^2}{2} B_{cath} = \mathcal{L}
\]

\(\sigma_0 = 1\text{ mm}\)

\(\varepsilon_{0x} = \varepsilon_{0y} = 1.074\text{ mm-mrad}\)

\(B_{cath} = 1.23 \text{ kG}\)
Non-magnetized beam (without space charge)

- Run with the baseline beam (non-magnetized, without space charge)

Slight increase in angular divergence.

\[ \text{std (}x\text{)} \]

\[ \Delta \varepsilon_x = 0.67 \times 10^{-6} \text{ m} \cdot \text{rad} \]

Spatial profile of the kicker?

\[ \varepsilon_x = 1.35 \times 10^{-6} \text{ m} \cdot \text{rad} \]

(ELEGANT: \[ 1.745 \times 10^{-6} \text{ m} \cdot \text{rad} \])
• Phase space and transverse distribution of non-magnetized beam

Initial phase distribution

Initial transverse distribution

Distribution after the kicker

Distribution after the kicker

Slight increase in size
Magnetization (without space charge)

Increase in angular divergence

$z - P^z_x$ plot maintains almost axially symmetric profile

$\Delta \varepsilon_x = 0.014 e^{-5} \text{ m}\cdot\text{rad}$

$\Delta \varepsilon_y = 0.009 e^{-5} \text{ m}\cdot\text{rad}$

$x$-Emittance

$\varepsilon_x = 3.422 e^{-5} \text{ m}\cdot\text{rad}$

$\varepsilon_y = 3.423 e^{-5} \text{ m}\cdot\text{rad}$

No change in beam size

Std ($x$)

$\varepsilon_z = 0.014 e^{-5} \text{ m}\cdot\text{rad}$

$\varepsilon_y = 0.009 e^{-5} \text{ m}\cdot\text{rad}$

$x$-Emittance

$\Delta \varepsilon_z = 3.432 e^{-5} \text{ m}\cdot\text{rad}$

$\Delta \varepsilon_y = 3.432 e^{-5} \text{ m}\cdot\text{rad}$
• Phase space and transverse distribution of magnetized beam

Initial phase distribution

Initial transverse distribution

Distribution after the kicker

Distribution after the kicker

Slight increase in size
3. EM design of the harmonic kicker
Design parameters of the QWR

- Initial parameters

\[ H = \frac{\lambda_1}{4} = 866 \text{ mm} \]

\[ b = \frac{\lambda_5}{4} = 96.2 \text{ mm} \quad \text{Maximum transit time factor} \]

\[ g = 2R_{bp} = 70 \text{ mm} \quad \text{Beam dynamics} \]

- The remaining geometry (a) is determined to minimize the total power \( P_d \).

\[ P_d = \sum_{n=1}^{5} \frac{V_n^2}{R_n} \]

\( V_n \): kick voltage by \( n \)-th mode

\( R_n \): transverse shunt impedance of \( n \)-th mode

\[
R_n = \frac{128\pi a^2 Z_0(a,b)^2 F_n^2(a,b) T_n^2(a,b)}{g^2 R_{sn} \lambda_{1} (1/a+1/b+8/\lambda_{1} \ln(b/a))}
\]

\( Z_0(a,b) = 60[\Omega] \ln (a/b) \) \quad \text{characteristic impedance}

\( R_{sn} = (\pi f_n \mu_0/\sigma)^{1/2} \) \quad \text{surface resistance of pure copper}

\( T_n(a,b) = \frac{\sin (2\pi f_n b/c)}{2\pi f_n b/c} \) \quad \text{transit time factor}

\( F_n(a,b) = b/a \) \quad \text{fringe field factor}
Power optimization by parameter scanning

- Analytical model by Gaussian profile
- Because exact formula for \( F_n \) and \( T_n \) are not available, the kick profile is modeled as a Gaussian whose \( rms \) and peak is fit from the CST simulation.

\[
F_n = \frac{1}{2a\varepsilon_n} \int_{-\infty}^{\infty} dz \, A_n e^{-\frac{z^2}{2\sigma_n^2}} = \frac{\sqrt{2\pi}\sigma_n A_n}{2a} \frac{\varepsilon_n}{\varepsilon_n}.
\]

\[
T_n = \frac{\int_{-\infty}^{\infty} dz \, A e^{-\frac{z^2}{2\sigma_n^2}} \cos 2\pi f_n \frac{z}{c}}{\int_{-\infty}^{\infty} dz \, A e^{-\frac{z^2}{2\sigma_n^2}}} = e^{-2\pi^2 \sigma_n^2 f_n^2 / c^2}
\]

![Graph showing shunt impedance of 5 modes and transverse shunt impedance (of the 5th mode).](image)

- Shunt impedance of 5 modes
- Transverse shunt impedance (of the 5th mode)
The power tends to be lower for the larger $b$ and smaller $\xi$. 

The total power
Parameter scan for minimum power loss

\[ \xi = -0.0133 \, b + 1.5838 \]

The power distribution on parameter space.

The power distribution near the threshold.
The constraints on the QWR

- With the analytically determined dimension, the initial sine

The axial profile of the $E_y$ field of 5th mode

The B field of the 5th-mode (TE11 mode)

<table>
<thead>
<tr>
<th>Modes</th>
<th>Kilpatrick limit</th>
<th>Peak Surface Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>86.6 MHz</td>
<td>11 MV/m</td>
<td>2.7 MV/m</td>
</tr>
<tr>
<td>259.8 MHz</td>
<td>16.5 MV/m</td>
<td>2.9 MV/m</td>
</tr>
<tr>
<td>433 MHz</td>
<td>20 MV/m</td>
<td>2.8 MV/m</td>
</tr>
<tr>
<td>606.2 MHz</td>
<td>23 MV/m</td>
<td>2.7 MV/m</td>
</tr>
<tr>
<td>779.4 MHz</td>
<td>26 MV/m</td>
<td>2.5 MV/m</td>
</tr>
</tbody>
</table>
Blending of the tip of the center conductor: 4~8mm

Power gain vs. height adjustment

Rough frequency tuning with height

- Target
- Rough frequency tuning with height

Tuning range

~180 W
Harmonic frequency tuning

- Linear approximation of frequency response to tapering
  \[ \Delta f_k = A_{ki} \Delta t p_i \]

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Cavity Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>86.6 MHz</td>
<td>Cavity with the tuners inserted</td>
</tr>
<tr>
<td>259.8 MHz</td>
<td>tp1 1.59 mm</td>
</tr>
<tr>
<td>433 MHz</td>
<td>tp2 -1.87 mm</td>
</tr>
<tr>
<td>606.2 MHz</td>
<td>tp3 -2.47 mm</td>
</tr>
<tr>
<td>779.4 MHz</td>
<td>tp4 0.38 mm</td>
</tr>
<tr>
<td></td>
<td>tp5 -1.53 mm</td>
</tr>
</tbody>
</table>

Graphs showing:
- Freq. sensitivity profile
- Freq. convergence with tapering iteration
Frequency control by tuner

- Linear approximation of frequency response to the tuner insertion

\[ \Delta f_k = B_{ki} \Delta t s_i \]

Tuning sensitivity matrix (around the default insertion depth \( l = 15 \text{ mm} \)) [MHz/mm]

\[
B = \begin{bmatrix}
-0.0169 & -0.0101 & -0.0032 & 0.0067 & 0.0082 \\
0.0050 & 0.0215 & -0.0270 & -0.0212 & 0.0141 \\
0.0375 & -0.0885 & -0.0001 & -0.0935 & -0.0135 \\
-0.0630 & -0.0116 & -0.0955 & -0.1116 & -0.0708 \\
-0.1909 & -0.0055 & 0.0316 & -0.0337 & -0.1513
\end{bmatrix}
\]

freq. sensitivity of the 4th mode. by the 2nd tuner stub

- The actual freq. change is non-linear and can only be effectively approximated by the method of iteration.

Constraints on tuners:

1. Thermal analysis to keep the temperature within reasonable range.
2. EBW needs some space between the tuners.
Field profile of the kicker

The field profiles of the kick as seen by the bunch (not scaled).

Contribution from $E_y$-field

Contribution from $B_x$-field

Other components are trivial.
Figures of merit for the harmonic kicker

<table>
<thead>
<tr>
<th>Modes</th>
<th>$f$ (MHz)</th>
<th>TTF</th>
<th>$R_{sh}$ (MΩ)</th>
<th>$P_d$ (kW)</th>
<th>$Q_0$</th>
<th>$\Delta f/f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>86.6</td>
<td>1</td>
<td>1.6</td>
<td>0.39</td>
<td>6.4E+03</td>
<td>±2E-04</td>
</tr>
<tr>
<td>2</td>
<td>259.8</td>
<td>0.98</td>
<td>0.8</td>
<td>0.77</td>
<td>1.11E+04</td>
<td>±1E-04</td>
</tr>
<tr>
<td>3</td>
<td>433</td>
<td>0.93</td>
<td>0.66</td>
<td>0.94</td>
<td>1.44E+04</td>
<td>±7E-05</td>
</tr>
<tr>
<td>4</td>
<td>606.2</td>
<td>0.87</td>
<td>0.62</td>
<td>1</td>
<td>1.72E+04</td>
<td>±6E-05</td>
</tr>
<tr>
<td>5</td>
<td>779.4</td>
<td>0.78</td>
<td>0.6</td>
<td>1</td>
<td>1.65E+04</td>
<td>±6E-05</td>
</tr>
</tbody>
</table>

$P_{tot}=4.1$ kW
Conclusion and outlook

• Preliminary beam dynamics with magnetized beam study has been done.
• With the solenoid turned on, space charge effect can be studied.
• Stability of the kick is to be investigated.
• The EM design of the kicker is near completion.
• The power coupler is to be developed.
Magnetized beam with space charge

- There was no significant change with space charge effect is turned on at 2nC bunch charge.

- With the solenoid turned off, the kick effect was studied.
  
  With the non-magnetized beam

  - Emittance
  - Spot size
  - Transverse distribution
  - Collective trajectory

  With the magnetized beam

  - Can the angular spread be controlled?
  - Does the emittance grow?
  - Is there significant difference between the non-magnetized and magnetized beam?
  - Is space charge effect significant?
  - What happens when the kicker is combined with the solenoid?