S2E Simulations on Jitter Tolerance for the European XFEL Project
- Optional Multi-Klystron Operation -

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New Lattice for TESLA XFEL – 4th Version

With TESLA XFEL Injector, $\varepsilon_n = 0.9$ μm

Q = 1.0 nC

$\sigma_z = 1.76$ mm $\rightarrow$ 113 μm $\rightarrow$ 23 μm

e-beam

RF-GUN $\rightarrow$ ACC1 $\rightarrow$ ACC2 $\rightarrow$ ACC3 $\rightarrow$ ACC4 $\rightarrow$ ACC39 $\rightarrow$ BC1 $\rightarrow$ BC2 $\rightarrow$ ACC5 $\rightarrow$ ACC6

60 MV/m 11.5 MV/m 20.5 MV/m 34.8 MV/m 20.65 MV/m
38 deg 25.0 MV/m -29.6 deg 160.6 deg $E = 510$ MeV
-18.3 deg $\sigma_\delta \sim 1.89$% $R_{56} = 87$ mm

To the end of Linac : ELEGANT with CSR

with geometric wakefields

ASTRA with Space Charge

0.0 m 12.0444 m

$\sigma_z = 20.5$ μm

FODO MODULES

ACC7 $\rightarrow$ ACC8 $\rightarrow$ ACC9 $\rightarrow$ ACC118

1567 m

UNDULATOR, 200 m

$E = 20.0$ GeV

$\sigma_\delta = 0.008$%

$\sigma_x = 37.3$ μm, $\sigma_y = 31.6$ μm, $\sigma_z = 20.5$ μm

$\varepsilon_{nx} = 1.5$ μm, $\varepsilon_{ny} = 0.94$ μm

All projected parameters !
New Klystron Layout for Jitter Study

Here K.No means Klystron number per module!

K.No = 1  2  1  1  1  2
One Klystron for 4 MODULES

One Klystron for 4 MODULES, Total 29 Klystrons

UNDULATOR, 200 m

Mlitli-Klystron before BC2 reduces the jitter sensitivity in ACC234 and ACC39 modules
Controllable Jitter Tolerance from Dr. Simrock

For both 1.3 GHz TESLA Module & 3.9 GHz 3\textsuperscript{rd} Harmonic Module

For the short term period (1 min)
RF Phase Error < 0.1 degree (rms)
RF Amplitude Error (dV/V) < 0.03\% (rms)

For the mid-term period (1 hour)
RF Phase Error < 0.3 degree (rms)
RF Amplitude Error (dV/V) < 0.09\%

Controllable jitter tolerance depends on charge fluctuation!

\[ Q = Q_0 (1 + 0.03\Delta \phi_i) (1 + (\Delta E / E)_r) (1 + (\Delta V / V)_g) \]

One feedback cycle: 10 \( \mu \)s + 4 \( \mu \)s delay = 14 \( \mu \)s

Dr. Simrock may improve these tolerances in the near future!
New Jitter Sensitivity Threshold

By the help of S2E simulations, let’s apply artificial jitter or error to all important components (GUN, ACC1 ~ ACC57, ACC39, BC1 and BC2) in order to investigate the sensitivity $p_{sensitivity}$ of those components on the longitudinal phase space at the end of linac.

New Jitter Sensitivity Threshold at the end of Linac:

- change in bunch length $\sigma_z$ within +10%
- change in beam energy within 0.005%
- change in peak-to-peak energy deviation ($\delta = dE/E$) within +0.1%
- change in bunch arrival time within 50 fs

Then choose the tolerance $p_{tolerance}$ which gives

$$\sqrt{\sum_{i=1}^{n} \left( \frac{P_{tolerance}}{P_{sensitivity}} \right)^2} < 1$$

Let’s check FEL performance under above tolerances with S2E simulations.
Most Sensitive Sources in $\delta = \frac{dE}{E}$ and $\sigma_s$

ACC2, ACC3, and ACC4 phase are the most sensitive jitter sources.

Sensitivity in energy deviation $\sim -0.375$ deg

Sensitivity in bunch length $\sim 0.065$ deg
Most Sensitive Sources in $\Delta E/E_o$ and $\Delta T_{\text{arrival}}$

ACC5678 dV/V is the most sensitive jitter sources in $\Delta E/E_o$
ACC2, ACC3, and ACC4 phase are the most sensitive jitter sources in $\Delta T_{\text{arrival}}$

Sensitivity in energy change $\sim 0.028\%$
Sensitivity in arrival time $\sim -0.056$ deg
## Sensitivity & Tolerance Set for each Klystron

For one macro pulse or one bunch train

<table>
<thead>
<tr>
<th></th>
<th>Sensitivity</th>
<th>Tol. Set A (rms)</th>
<th>Tol. Set B (rms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>dT</td>
<td>0.50 ps</td>
<td>0.1 ps</td>
<td>0.3 ps</td>
</tr>
<tr>
<td>dQ</td>
<td>-6.10%</td>
<td>1.0%</td>
<td>1.5%</td>
</tr>
<tr>
<td>ACC1C1234 Phase</td>
<td>0.20 deg</td>
<td>0.05 deg</td>
<td>0.07 deg</td>
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<tr>
<td>ACC1C1234 dV/V</td>
<td>-0.17%</td>
<td>0.02%</td>
<td>0.03%</td>
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<tr>
<td>ACC1C5678 Phase</td>
<td>0.10 deg</td>
<td>0.05 deg</td>
<td>0.07 deg</td>
</tr>
<tr>
<td>ACC1C5678 dV/V</td>
<td>-0.08%</td>
<td>0.02%</td>
<td>0.03%</td>
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<tr>
<td>ACC234 Phase</td>
<td>-0.056 deg</td>
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<td>0.07 deg</td>
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<tr>
<td>ACC234 dV/V</td>
<td>-0.06%</td>
<td>0.02%</td>
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<tr>
<td>ACC39 Phase</td>
<td>-0.08 deg</td>
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<tr>
<td>ACC39 dV/V</td>
<td>0.19%</td>
<td>0.02%</td>
<td>0.03%</td>
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<tr>
<td>BC1 dI/I</td>
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<tr>
<td>BC2 dI/I</td>
<td>0.31%</td>
<td>0.02%</td>
<td>0.02%</td>
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<tr>
<td>ACC5678 Phase</td>
<td>4.19 deg</td>
<td>0.05 deg</td>
<td>0.07 deg</td>
</tr>
<tr>
<td>ACC5678 dV/V</td>
<td>0.028%</td>
<td>0.02%</td>
<td>0.03%</td>
</tr>
</tbody>
</table>
S2E Simulations with 331 Random Error Set A

Median: 20.006 GeV
RMS Error: 0.0057%
S2E Simulations with 331 Random Error Set A

Median : 19.1 μm
RMS Error : 18.3%
S2E Simulations with 331 Random Error Set A

Median : 0.0086%
RMS Error : 0.0019%
S2E Simulations with 331 Random Error Set A

Median : 5.217 µs
RMS Error : 97 fs
S2E Simulations with 331 Random Error Set A

Median : 4.71 μm
RMS Error : 206%
S2E Simulations with 331 Random Error Set A

Median : 3.93E-8
RMS Error : 280%

\[
\Delta \langle xp \rangle / \langle xp \rangle_0 (\%)
\]
S2E Simulations with 331 Random Error Set A

Median : -0.048 μm
RMS Error : 0.05%
S2E Simulations with 331 Random Error Set A

Median : 1.77E-9
RMS Error : 0.057%
For 80% core slices
Median : 0.933 μm
RMS Error : 2.47%
S2E Simulations with 331 Random Error Set A

For whole bunch
Median : 171 m
RMS Error : 5.8%
S2E Simulations with 331 Random Error Set A

For 80% core slices
Median : 107 m
RMS Error : 6.9%
S2E Simulations with 331 Random Error Set A

For 80% core slices
Median : 1.00924 Å
RMS Error : 0.012%
S2E Simulations with 331 Random Error Set A

For whole bunch
Median : 46.9 GW
RMS Error : 38%
S2E Simulations with 331 Random Error Set A

For 80% core slices
Median : 50.6 GW
RMS Error : 39.7%
S2E Simulations with 327 Random Error Set B

Median : 20.0059 GeV
RMS Error : 0.009%
S2E Simulations with 327 Random Error Set B

Median : 19.1 μm
RMS Error : 25.2%
Median: 5.217 μs
RMS Error: 124 fs
For whole bunch
Median : 172 m
RMS Error : 7.5%
S2E Simulations with 327 Random Error Set B

For 80% core slices:
- Median: 50.8 GW
- RMS Error: 76.9%
After considering the space charge force at Gun, CSR in BCs, and geometric wakefields in linac, we have investigated jitter tolerance in the new TESLA XFEL lattice.

At the moment, it seems that we may control phase jitters by the multi-klystron operation before BC2.

The most difficult points are ACC234 phase and ACC5678 dV/V

We should discuss these results with respect to users aspect (specially power).
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