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

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New Lattice for TESLA XFEL – 4th Version

With TESLA XFEL Injector, $\varepsilon_n = 0.9$ $\mu$m

Q = 1.0 nC

e-beam

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

60 MV/m
38 deg

11.5 MV/m
25.0 MV/m
-18.3 deg

20.5 MV/m
-29.6 deg

34.8 MV/m
160.6 deg

$E = 510$ MeV
$\sigma_\delta \approx 1.89\%$
$R_{56} = 87$ mm
$\theta = 3.95$ deg

$E = 510$ MeV
$\sigma_\delta \approx 1.88\%$
$R_{56} = 4.8$ mm
$\theta = 0.93$ deg

20.65 MV/m
0.0 deg

$\sigma_z = 20.5$ $\mu$m

FODO MODULES

ACC7  ACC8  ACC9  ACC57

1567 m

UNDULATOR, 200 m

$E = 20.0$ GeV
$\sigma_\delta = 0.008\%$
$\sigma_x = 37.3$ $\mu$m, $\sigma_y = 31.6$ $\mu$m, $\sigma_z = 20.5$ $\mu$m
$\varepsilon_{nx} = 1.5$ $\mu$m, $\varepsilon_{ny} = 0.94$ $\mu$m

ASTRA with Space Charge

0.0 m 12.0444 m

To the end of Linac : ELEGANT with CSR

with geometric wakefields without space charge

TeV-Energy Superconducting Linear Accelerator Projects - TTF-2, TESLA X-ray FEL, TESLA Linear Collider
4th Lattice with TESLA XFEL Injector Layout

With TESLA XFEL Injector, \( \varepsilon_n = 0.9 \, \mu m \)

Simulated Particles = 200000

END of LINAC with 60 slices

5.0 kA
4th Lattice with TESLA XFEL Injector Layout

With TESLA XFEL Injector, $\varepsilon_\text{n} = 0.9 \mu$m

Normalized Emittance - X (m)

Simulated Particles = 200000

END of LINAC with 60 slices

1.4 \mu m
4th Lattice with TESLA XFEL Injector Layout

With TESLA XFEL Injector, $\varepsilon_n = 0.9 \mu m$

![Normalized Emittance Graph](image)

- Simulated Particles = 200000
- END of LINAC with 60 slices

1.4 $\mu m$
4th Lattice with TESLA XFEL Injector Layout

With TESLA XFEL Injector, $\varepsilon_n = 0.9 \, \mu m$

Maximum uncorrelated energy spread : $0.997 \, \text{MeV} \at \text{20.0 GeV} \approx 0.00498\% < 0.0125\%$

Fortunately, the uncorrelated energy spread in the center region is around $0.0005\%$
Old Klystron Layout for Jitter Study

Here K.No means Klystron number per module!

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

One Klystron for 4 MODULES

We met difficulty in ACC234 phase (0.02 degree) and ACC39 phase (-0.04 degree)!
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

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 3rd 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%

For the mid-term period (1 day)
RF Phase Error < 1.0 degree (rms)
RF Amplitude Error (dV/V) < 0.3%

Dr. Simrock will improve these tolerances in the near future!

Reference !!!
Jitter Investigation Method with S2E simulation

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 $p_{\text{sensitivity}}$ of those components on the longitudinal phase space at the end of linac (bunch length and dE/E).

After considering FEL performance, let’s choose the tightest $p_{\text{sensitivity}}$ by limiting

change in bunch length within $+10\%$ (~ 2 μm) at the end of linac
change in dE/E within $+0.1\%$ at the end of linac

Then choose the tolerance $p_{\text{tolence}}$ which gives

$$\sqrt{\sum_{i=1}^{n} \left( \frac{p_{\text{tolence}}}{p_{\text{sensitivity}}} \right)^2} < 1$$

Let’s check FEL performance under above tolerances with S2E simulations.
(Next week will report this !)
Jitter Sensitivity Investigation Method

Used macro particle number for jitter sensitivity investigation : 10000

Considered Collective Effects : Space charge, CSR, Geometric Wakefields.

BINs for CSR calculation is reduced to control the artificial modulation at BCs due to small particle number.

Here dE/E means the relative energy deviation (peak-to-peak) at the end of linac.

For each jitter sensitivity investigation, 10 S2E simulations are used.
S2E simulation Results - Sensitivity

**Gun Timing Jitter**

![Graph showing Gun Timing Jitter Sensitivity](image)

- Sensitivity in dE/E $\sim -11.0$ ps
- Sensitivity in bunch length $\sim 1.0$ ps

Therefore the tightest sensitivity is about 1.0 ps
S2E simulation Results - Sensitivity

Change in Charge Q at Gun

From LEUTL’s photoinjector experiences,

\[ Q = Q_0 (1 + 0.03 \Delta \phi) (1 + (\Delta E / E)_{l} ) (1 + (\Delta V / V)_{s} ) \]

\[
\begin{align*}
\text{Sensitivity in } dE/E & \sim -40\% \\
\text{Sensitivity in bunch length} & \sim 8\%
\end{align*}
\]

Therefore the tightest sensitivity is about 8\%
S2E simulation Results - Sensitivity

ACC1C1234 RF Phase
Here we assumed ACC1C1234 will be driven by one Klystron

Sensitivity in dE/E ~ -2 degree
Sensitivity in bunch length ~ 0.2 degree

Therefore the new (old) tightest sensitivity is about 0.2 degree (0.1 degree)
S2E simulation Results - Sensitivity

ACC1C1234 RF Phase
Here we assumed ACC1C1234 will be driven by one Klystron

(New Klystron Layout)  (Old Klystron Layout)

Therefore the tightest sensitivity in ACC1C1234 phase is about 0.2 degree
S2E simulation Results - Sensitivity

ACC1C1234 RF Voltage dV/V
Here we assumed ACC1C1234 will be driven by one Klystron

![Graph showing sensitivity in dE/E ~ -6.25%]

![Graph showing sensitivity in bunch length ~ 0.6%]

Therefore the new (old) tightest sensitivity is about 0.6% (0.15%)
S2E simulation Results - Sensitivity

ACC1C5678 RF Phase
Here we assumed ACC1C5678 will be driven by one Klystron

![Graph showing dE/E vs. change in ACC1C5678 phase (deg)](image1)

Sensitivity in dE/E ~ -0.63 degree

![Graph showing σ_s vs. change in ACC1C5678 phase (deg)](image2)

Sensitivity in bunch length ~ 0.1 degree

Therefore the tightest sensitivity is about 0.1 degree
S2E simulation Results - Sensitivity

**ACC1C5678 RF Voltage dV/V**
Here we assumed ACC1C5678 will be driven by one Klystron

Sensitivity in \( \frac{dE}{E} \sim -6.0\% \)

Sensitivity in bunch length \( \sim 0.6\% \)

Therefore the tightest sensitivity is about \( 0.6\% \)
S2E simulation Results - Sensitivity

ACC2, ACC3, and ACC4 RF Phase
Here we assumed ACC2, ACC3, and ACC4 will be driven by three Klystrons

ACC3 and ACC4 have the same sensitivity

Sensitivity in dE/E ~ -0.4 degree

Sensitivity in bunch length ~ 0.05 degree

Therefore the new (old) tightest sensitivity is about 0.05 degree (0.02 degree)
S2E simulation Results - Sensitivity

ACC2, ACC3, and ACC4 RF Phase
Here we assumed ACC2, ACC3, and ACC4 will be driven by three Klystrons

(New Klystron Layout)

(Old Klystron Layout)

Therefore the tightest sensitivity is about 0.05 degree
ACC2, ACC3, and ACC4 RF Voltage dV/V
Here we assumed ACC2, ACC3, and ACC4 will be driven by three Klystrons

ACC3 and ACC4 have the same sensitivity

Sensitivity in dE/E ~ -4%
Sensitivity in bunch length ~ 0.25%

Therefore the new (old) tightest sensitivity is about 0.25% (0.1%)
S2E simulation Results - Sensitivity

ACC39C1234 and ACC39C5678 RF Phase
Here we assumed ACC39 will be driven by two Klystrons

ACC39C1234 has the same sensitivity

Sensitivity in $dE/E \sim 0.4$ degree
Sensitivity in bunch length $\sim -0.1$ degree

Therefore the new (old) tightest sensitivity is about $-0.1$ degree ($-0.04$ degree)
S2E simulation Results - Sensitivity

ACC39C1234 and ACC39C5678 RF Phase
Here we assumed ACC39 will be driven by two Klystrons

(New Klystron Layout)

(Old Klystron Layout)

Therefore the tightest sensitivity is about -0.1 degree
S2E simulation Results - Sensitivity

ACC39C1234 and ACC39C5678 RF Voltage dV/V
Here we assumed ACC39 will be driven by two Klystrons

ACC39C1234 has the same sensitivity

<table>
<thead>
<tr>
<th>Sensitivity in dE/E</th>
<th>Sensitivity in bunch length</th>
</tr>
</thead>
<tbody>
<tr>
<td>~ -10%</td>
<td>~ -5.4%</td>
</tr>
</tbody>
</table>

Therefore the new (old) tightest sensitivity is about -5.4% (~3.0%)
S2E simulation Results - Sensitivity

BC1 Power Supply Error $dI/I = dB/B$

Here we assumed BC1 will be driven by one power supply

Sensitivity in $dE/E \sim 0.5\%$

Sensitivity in bunch length $\sim -0.05\%$

Therefore the tightest sensitivity is about $-0.05\%$
S2E simulation Results - Sensitivity

BC2 Power Supply Error $dI/I=dB/B$
Here we assumed BC2 will be driven by one power supply

![Graph 1](image1.png)
![Graph 2](image2.png)

Sensitivity in $dE/E \sim 125\%$
Sensitivity in bunch length $\sim -1\%$

Therefore the tightest sensitivity is about $-1\%$
S2E simulation Results - Sensitivity

**ACC5678 RF Phase**

We assumed ACC5, ACC6, ACC7, and ACC8 will be driven by one Klystron. Since there are about 26 Klystrons after BC2, this region is safe against jitter.

![Graph 1](0.0830, 0.0835, 0.0840, 0.0845, 0.0850)

- **Sensitivity in dE/E ~ -40 degree**

![Graph 2](18.0, 18.2, 18.4, 18.6, 18.8)

- **Sensitivity in bunch length ~ ∞**

Therefore the tightest sensitivity is about ~-40 degree
S2E simulation Results - Sensitivity

ACC5678 RF Voltage dV/V
We assumed ACC5, ACC6, ACC7, and ACC8 will be driven by one Klystron
Since there are about 26 Klystrons after BC2, this region is safe against jitter.

Sensitivity in \( \frac{dE}{E} \sim \infty \) degree

Therefore the tightest sensitivity is about \( \infty \) degree
Sensitivity & Tolerance

Now ACC2, ACC3, and ACC4 phase (0.05 degree) are close to our control range!

<table>
<thead>
<tr>
<th></th>
<th>Sensitivity (rms)</th>
<th>Tolerance (rms) for 1 minute</th>
</tr>
</thead>
<tbody>
<tr>
<td>dT</td>
<td>1.0 ps</td>
<td>0.3 ps</td>
</tr>
<tr>
<td>dQ</td>
<td>8.0%</td>
<td>1.0%</td>
</tr>
<tr>
<td>ACC1C1234 Phase</td>
<td>0.2 deg</td>
<td>0.05 deg</td>
</tr>
<tr>
<td>ACC1C1234 dV/V</td>
<td>0.6%</td>
<td>0.03%</td>
</tr>
<tr>
<td>ACC1C5678 Phase</td>
<td>0.1 deg</td>
<td>0.05 deg</td>
</tr>
<tr>
<td>ACC1C5678 dV/V</td>
<td>0.6%</td>
<td>0.03%</td>
</tr>
<tr>
<td>ACC234 Phase</td>
<td>0.05 deg</td>
<td>0.05 deg</td>
</tr>
<tr>
<td>ACC234 dV/V</td>
<td>0.25%</td>
<td>0.03%</td>
</tr>
<tr>
<td>ACC39 Phase</td>
<td>0.1 deg</td>
<td>0.05 deg</td>
</tr>
<tr>
<td>ACC39 dV/V</td>
<td>5.4%</td>
<td>0.03%</td>
</tr>
<tr>
<td>BC1 dI/I</td>
<td>0.05%</td>
<td>0.02%</td>
</tr>
<tr>
<td>BC2 dI/I</td>
<td>1.0%</td>
<td>0.02%</td>
</tr>
<tr>
<td>ACC5678 Phase</td>
<td>-</td>
<td>0.05 deg</td>
</tr>
<tr>
<td>ACC5678 dV/V</td>
<td>-</td>
<td>0.03%</td>
</tr>
</tbody>
</table>
Saturation length is safe enough (< 200 m) under jitters and errors !!!
Old S2E simulation Results – Tolerance

Wavelength is no problem but the jitter in the saturation power is high !!!

Planned Power ~ 24 GW

~ 1.0 Å

100 GW

1.0 GW
Summary

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.

Next week, I will report on the tolerance study with 100 random error set.
Y. Kim sincerely thanks S. Simrock, M. Borland, P. Emma, S. Schreiber, J. S. Oh, Professor J. Rossbach, Professor I. S. Ko, and Professor W. Namkung for their encouragements of this work and many useful comments and discussions on the injector and BC layout.