Performance Comparison of S-band, C-band, and X-band RF Linac based XFELs

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Outline

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☐ C-band based XFEL Driving Linac

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  ● Sensitivities of RF Jitters
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☐ Several Directions for Stable Compact XFEL Driving Linac

☐ Summary
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Acceleration - Traveling Wave (TW) Accelerator

To avoid any arc between two electrodes, and to get a much higher beam energy gain, we use an Alternating Current (AC) type accelerator → RF Accelerator.

To get the best acceleration, we need a good synchronization between charged beams and RF wave (phase velocity of electromagnetic wave = velocity of electron beams).

→ Principle of Traveling Wave (TW) Accelerator, whose position of electromagnetic wave is continuously moving.

\[ \nu_w = \frac{d}{t} \]

\[ 2\pi/4 \text{ mode TW structure} \]
**Radio Frequency (RF)** is a rate of oscillation of electromagnetic waves in the range of about 30 kHz to 300 GHz. **Frequency Ranges of Microwaves** = 300 MHz to 300 GHz.

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**IEEE US Bands**
- 30 - 300 kHz : LF-band
- 300 - 3000 kHz : MF-band
- 3 - 30 MHz : HF-band
- 30 - 300 MHz : VHF-band
- 300 - 1000 MHz : UHF-band

**American / European Frequencies**
- S-band : 2856 MHz / 2998 MHz
- C-band : 5712 MHz / 5996 MHz
- X-band : 11424 MHz / 11992 MHz
Short-Range Wakefields in Linac Accelerators

If an electron bunch moves in a periodic linac structure, there are interactions between the electrons in a bunch and the linac structure, which induce changes in beam energies and beam divergences ($x'$ and $y'$) of electrons in the same bunch. We call these interactions between electrons in the same bunch and the linac structure as the short-range wakefields, which change beam energy spread and emittance of the bunch.

blue: an interaction between an electron at the head region and a linac structure.

pink: short-range wakefield from the linac structure to a following electron at the tail region.

A. Chao's Handbook of Accelerator Physics & Engineering, p. 252
SLAC-AP-103 (LIAR manual)
Short-Range Wakefields in Linac Accelerators

Energy loss $\delta E_i$ of a test electron (or slice) $i$ in a bunch due to the short-range longitudinal wake function $W_L(s)$, which is induced by all other preceding electrons $j$ located at $s = |i - j|$ distance from the test electron $i$ is given by

$$\delta E_i = \left[ \frac{W_L(0)}{2} |q_i| + \sum_{j=1}^{i-1} W_L(i - j) \cdot q_j \right] \cdot L .$$

Here $q_i$ and $q_j$ are charge of electron (or slice) $i$ and $j$, and $L$ is the length of the linac structure. $i$ or $j = 1$ means the head electron in the bunch, and the sum term is only evaluated for $i > 1$.

The transverse trajectory deflection angle change $\delta x_i'$ of a test electron $i$ due to the short-range transverse wake function $W_T(s)$, which is excited by all preceding electrons $j$ is given by

$$\delta x_i' = \sum_{j=1}^{i-1} q_j x_j L W_T(i - j) .$$

Here the sum term is only evaluated for $i > 1$.
Longitudinal Short-Range Wakefields

Longitudinal wake function $W_L(s)$ of the test particle in a bunch is the voltage loss experienced by the test charged particle. The unit of $W_L(s)$ is [V/C] for a single structure or [V/C/m] for a periodic unit length. The longitudinal wake is zero if test particle is in front of the unit particle ($s < 0$). For a bunch of longitudinal charge distribution $\lambda_z$, the bunch wake $\mathcal{W}(s)$ (= voltage gain for the test particle at position $s$) is given by

$$\mathcal{W}(s) = - \int_0^\infty W_L(s') \lambda_z(s - s') ds'$$

And the minus value of its average $-\langle \mathcal{W} \rangle$ gives the loss factor and its rms $\mathcal{W}_{rms}$ gives energy spread increase: $\Delta E_{rms} = eNL\mathcal{W}_{rms}$

where $L$ is the length of one period cell, $N$ is the number of electrons in the bunch.

a unit charged particle moving with $v \sim c$

a test charged particle with a distance $s$ away from the unit charged particle and moving with $v \sim c$
Longitudinal Short-Range Wakefields

Phase Space after Unit-I C-band Linac with/without Short Range Wakefield

- Red: without short-range wakefield
- Green: with short-range wakefield

→ increased nonlinearity in longitudinal phase space

A unit charged particle moving with $v \sim c$

A test charged particle with a distance $s$ away from the unit charged particle and moving with $v \sim c$

SLAC-AP-103 (LIAR manual)
SLAC-PUB-11829
SLAC-PUB-9798
TESLA Report 2004-01
TESLA Report 2003-19
Longitudinal Short-Range Wakefields

Longitudinal impedance is the Fourier transformation of the longitudinal wake function:

\[ Z(k) = \frac{1}{c} \int_{0}^{\infty} W_L(s)e^{iks}ds \]

Yokoya's wakefield model for periodic linac structure:

\[ W_L(s) = \frac{cZ_0}{\pi a^2} \left[ 1 + W_{L1}\sqrt{\zeta} + W_{L2}\zeta + W_{L3}\zeta^2 \right] \]
\[ W_T(s) = \frac{cZ_0}{\pi a^4} s \left[ 2 + W_{T1}\sqrt{\zeta} + W_{T2}\zeta + W_{T3}\zeta^2 \right] \]

\[ W_{L1} = -1.614r^{0.122}, \quad W_{L2} = +1.012r^{0.169}, \quad W_{L3} = -0.231r^{0.111} \]
\[ W_{T1} = -2.781r^{0.217}, \quad W_{T2} = +1.637r^{0.511}, \quad W_{T3} = -0.364r^{0.793} \]

\[ \zeta = \frac{Ls}{a^2} \quad r = \frac{a/\lambda}{0.15}. \]
PSI S-band Linac Structure

PSI 4.3 m long $2\pi/3$ S-band TW Structure
- RF Frequency = 2997.924 MHz
- average inner diameter $2a = 22.005$ mm
- average outer diameter $2b = 80.302$ mm
- period $p = 33.333$ mm
- iris thickness $t = 5$ mm
- cell number for 4.3 m structure = 122
- average shunt impedance = 59 MΩ/m
- filling time = 900 ns
- attenuation factor ~ 0.6
- RF pulse length = 4 µs
- required RF power for 25 MV/m = 60 MW
- one 45 MW klystron + SLED with 2.5 power gain can drive 2 structures.

This structure is used for linac Optimization-I and Optimization-III.
Original PSI S-band RF Option

To drive two 4.3 m long S-band Structures
klystron maximum output power = 45 MW
klystron operational power before SLED with 15% margin = 38 MW
klystron pulse length before SLED ~ 4.0 μs
modulator maximum power ~ 100 MW
SLED power gain with a SLED loss and a 15% power margin ~ 2.5
d power after SLED with a SLED loss + a power margin = 94 MW
power per structure with a SLED loss + a margin = 47 MW
energy gain per structure with a SLED loss + a margin = 95 MeV
gradient with a SLED loss + power margin = 22 MV/m
energy gain per modulator with a SLED loss and a 15% power
margin = 189 MeV
structure filling time = 0.9 μs
number of structures per modulator = 2
number of structures for 6 GeV with on-crest RF phase = 64
number of modulators for 6 GeV with on-crest RF phase = 32
number of klystrons for 6 GeV with on-crest RF phase = 32
length of one FODO cell = 10.4 m
total length of 6 GeV linac with on-crest RF phase = 332.8 m
sensitivity of modulator error = somewhat low due to low SLED-gain

Yujong Kim @ Idaho State University and Thomas Jefferson National Accelerator Facility, USA
C-band TW RF Linac

Frequency: 5712 MHz
Phase shift per cell: 3\pi/4
Field distribution: semi C.G.
Number of cells: 91 cell
Active length: 1791 mm
Iris aperture (2a): up-stream 17.4 mm, down-stream 12.5 mm
Cavity diameter: up-stream 45.3 mm, down-stream 43.3 mm
Disk thickness: t 3.0 mm
Quality factor: Q 10.7-1 \times 10^3, 0.3
Group velocity: up-stream 0.035 c, down-stream 0.012 c
Average shunt impedance: rs 53-67 M\Omega/m
Attenuation parameter: 0.53
Filling time: T_f 286 nsec

$2a \sim 14$ mm for SCSS structure
$2b \sim 40$ mm
Period $p \sim 16.7$ mm, $t \sim 2.5$ mm

Yujong Kim @ Idaho State University and Thomas Jefferson National Accelerator Facility, USA
C-band TW RF Linac

Let's thank to C-band RF Pioneers
Prof. H. Matsumoto of KEK
Prof. T. Shintake of RIKEN/SPring-8

Yujong Kim @ Idaho State University and Thomas Jefferson National Accelerator Facility, USA
260 m long C-band RF LINAC for XFEL/SPring-8
RF Option for C-band TW RF Linac

To drive two 2 m long C-band Structures

- Klystron maximum output power = 50 MW
- Klystron operational power before SLED with 24% power margin = 38 MW
- Klystron pulse length before SLED = 2.5 µs
- Modulator maximum power ~ 100 MW
- SLED power gain with a SLED loss ~ 2.63
- Power after SLED with a SLED loss + 24% margin = 100 MW
- Power per structure with a SLED loss + 24% margin = 44 MW
- Energy gain per structure with a SLED loss + 24% margin = 60 MeV
- Gradient with a SLED loss + 24% margin = 30.0 MV/m
- Energy gain per modulator with a SLED loss + 24% margin = 120.0 MeV
- Structure filling time = 0.300 µs
- Number of structures per modulator = 2
- Number of structures for 6 GeV with on-crest RF phase = 100
- Number of modulators for 6 GeV with on-crest RF phase = 50
- Number of klystrons for 6 GeV with on-crest RF phase = 50
- Length of one half FODO cell = 4.95 m
- Length of one FODO cell = 9.9 m
- Total length of 6 GeV linac with on-crest RF phase = 247.5 m
- Sensitivity of modulator error = low due to low SLED gain and many RF stations.

Yujong Kim @ Idaho State University and Thomas Jefferson National Accelerator Facility, USA
X-band TW Linac for SwissFEL

X-band Linac Structure with Alignemnt Monitor

- developed with collaboration with CERN, ELETTRA & PSI
- original model: SLAC H75 type.
- resonance frequency: ~ 11991.648 MHz
- phase advance: $5\pi/6$
- cell number: 72
- active length: 750 mm
- average iris diameter $2a$: 9.1 mm
- average outer diameter $2b$: 21.4267 mm
- cell length $p$: 10.4104 mm
- iris thickness $t$: 1.6963 mm
- filling time: 100 ns
- average gradient: 40 MV/m for 33 MeV with 35.1 MW
- sensitivity: 1.53 dB/mm for 200 pC
- cell 36 and 63 have radial coupling waveguides to extract dipole mode signals, which can be used to structure alignment
- expected alignment resolution $\leq$ 5 µm (rms)
- available signals: tilt, bend, offset, cell-to-cell misalignment

Courtesy of M. Dehler

63th cell with radial coupling waveguides

Yujong Kim @ Idaho State University and Thomas Jefferson National Accelerator Facility, USA
RF Option for X-band TW RF Linac

To drive six 0.75 m long X-band Structures

- Klystron maximum output power = 50 MW
- Klystron operational power before SLED with 10% power margin = 45 MW
- Klystron pulse length before SLED = 1.5 µs
- Modulator maximum power ~ 100 MW
- SLED power gain with a SLED loss ~ 4.8
- Power after SLED with a SLED loss + 10% power margin = 220 MW

- Power per structure with a SLED loss + 10% margin = 35 MW
- Energy gain per structure with a SLED loss + 10% margin = 33 MeV
- Gradient with a SLED loss + 10% margin = 44 MV/m
- Energy gain per modulator with a SLED loss + 10% margin = 198 MeV
- Structure filling time = 100 ns
- Number of structures per modulator = 6
- Number of structures for 6 GeV with on-crest RF phase = 186
- Number of modulators for 6 GeV with on-crest RF phase = 31
- Number of klystrons for 6 GeV with on-crest RF phase = 31
- Length of one FODO cell = 7.89 m
- Total length of 6 GeV linac with on-crest RF phase = 244.59 m
- Sensitivity of modulator error = high due to high SLED-II gain & smaller RF stations.

Note that one X-band klystron (SLED-II) is about 3 times (2 times) expensive than those of S and C bands.

Yujong Kim @ Idaho State University and Thomas Jefferson National Accelerator Facility, USA
Short-Range Wakefields of S-, C-, and X-band Linacs

**Longitudinal Short-Range Wakefields:** Strong if bunch length is short (after BC2). A higher RF frequency linac with a stronger longitudinal short-range wakefield is better after BC2 for effective control of energy chirp.

**Transverse Short-range Wakefields:** Strong if bunch length is longer (before BC1). Impact of the transverse short-range wakefields after BC2 is weak enough even though we use a high frequency RF linac after BC2.
Performance of X-band based LINAC2

Performance of Optimization-XIX is exactly same as that of Optimization-III!

due to near on-crest operation at LINAC2, sensitivity of RF phase error becomes weaker!
149 m shorter than Optimization-III

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Yujong Kim @ Idaho State University and Thomas Jefferson National Accelerator Facility, USA
RF Amplitude & Phase for Chirping Control

X-band based SwissFEL Optimization-XIX

Gradient: 40 MV/m
Phase: +5 deg
$\sigma_\delta = 0.074\%$

Gradient: 40 MV/m
Phase: -5 deg
$\sigma_\delta = 0.032\%$

Gradient: 44 MV/m
Phase: -5 deg
$\sigma_\delta = 0.024\%$
Impact of Energy Chirping on XFEL Photons

From our recent full S2E simulations with ASTRA, ELEGANT, and GENESIS codes (Y. Kim and S. Reiche), we confirmed that we can effectively minimize the bandwidth of XFEL photon beams by optimizing energy chirping of electron beams.

Optimization-III, VI, VII chirp for $I_{pk} = 1.6$ kA

Optimization-V chirp for $I_{pk} = 2.7$ kA

Saturation Length < 50 m !!!

Optimization-III & V
S-band based Linacs
Linac Length = 650 m

Optimization-VI & VII
C-band based Linacs
Linac Length = 540 m, 510 m

wavelength = 0.1 nm @ FEL1
no of photon per pulse ~ $1.0 \times 10^{11}$
saturation length ~ 40 m with 2.7 kA
saturation length ~ 48 m with 1.6 kA

Yujong Kim @ Idaho State University and Thomas Jefferson National Accelerator Facility, USA
Energy Chirp Control with S-band Linac

ASTRA up to exit of SB02 & ELEGANT from exit of SB02 to consider space charge, CSR, ISR, and wakefields!

SwissFEL Optimization-I with S-band RF Linacs

SwissFEL Optimization-III with a longer S-band RF Linacs for Chirp Compensation

Yujong Kim @ Idaho State University and Thomas Jefferson National Accelerator Facility, USA
SwissFEL - S-band based LINAC2 after BC2

LINAC2 for Optimization-III

QF 4.3 m long S-band Tube QD 4.3 m long S-band Tube

2998 MHz S-band Tube 0.7 m long diagnostic section

22 MV/m

0.2 m long QM 0.2 m long QM

One FODO Cell for LINAC2 = 10.4 m

length of one FODO cell in LINAC2
= two 4.3 m long PSI standard S-band tubes
+ two 0.7 m long PSI standard diagnostic sections
+ two 0.2 m long QMs = 10.4 m

pure active length per tube = 4.073032 m
number of cell per tube = 122 including two coupler cells
central cell length = 33.333 mm
iris diameter = 25.4 mm
total cells in LINAC2 = 34 FODO cells
No. of S-band tubes = SB23-SB90 for 34 FODO cells
total needed S-band tubes in LINAC2 = 68
total needed RF stations = 34 with two tubes per station
total needed QMs in LINAC2 = 2x34 = 68
total length of LINAC2 = 353.6 m

Optics for S-band Based LINAC2

Yujong Kim @ Idaho State University and Thomas Jefferson National Accelerator Facility, USA
SwissFEL - Performance of S-band LINAC2

LINAC2 for Optimization-III

\[ \sigma_\delta \approx \frac{(1+0.25i)9.55e_0Nf_0W_{||}(1.3\sigma_z) - 2.35\sigma_z k_{rf} G \sin \phi_{rf}}{2.35G \cos \phi_{rf}} \]

\[ W_{||}(z) \approx \frac{Z_0c}{\pi a \sqrt{a^2 + 8z\lambda_{rf}}} \] (V/C/m); long. wakefield

\( \phi_{rf} \) giving minimum \( \sigma_\delta \) is determined when \( \text{Re}(\sigma_\delta) = 0 \)

Optimization - III, \( \phi_{rf} \sim 40 \) degree

due to far off-crest operation at LINAC2, sensitivity of RF phase error becomes stronger!

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Performance of S-band based LINAC2

Slice Parameters at the end of LINAC2 (~ 6 GeV) of Optimization-III

\[ I_{\text{peak}} < 1.6 \text{kA for } |dz| < 20 \mu \text{m} \]

\[ \varepsilon_{n,\text{slice}} < 0.33 \mu \text{m for } |dz| < 20 \mu \text{m} \]

\[ \sigma_{dE,\text{slice}} < 148 \text{ keV for whole bunch} \]
\[ \sigma_{dE,\text{slice}} < 29.8 \text{ keV for } |dz| < 20 \mu \text{m} \]

from uncorrelated energy spread

all slice parameters at FEL1, FEL2, and FEL3 are similar to these.
S-band LINAC2 - $\Delta \phi_{\text{rf}}$ Sensitivity

(top left) change of longitudinal phase space, (top right), change of projected relative energy spread, (bottom left) change of beam energy when RF phase of an RF station in S-band LINAC2 is changed by $\pm 1.2$ deg (= 0.4 deg in rms) with five steps (step size = 0.6 deg). please note that $\pm 1.2$ deg in S-band RF system corresponding to about $\pm 1.2$ ps.

dE $\sim 27.9$ MeV for 2.4 ps, dE $\sim 11.6$ MeV for 1.0 ps
dE/E $\sim 0.19\%$ for $\Delta \phi_{\text{rf}} = 1.0$ deg (= 1 ps)
energy spread change $\sim 0.5\%$ for $\Delta \phi_{\text{rf}} = 1.0$ deg
In this case, XFEL wavelength change $\sim 0.38\%$

at the end of LINAC2 for five $\Delta \phi_{\text{rf}}$ changes

big change of beam energy against $\Delta \phi_{\text{rf}}$! phase error sensitivity is higher due to far off-crest operation at S-band LINAC2.

Yujong Kim @ Idaho State University and Thomas Jefferson National Accelerator Facility, USA
S-band LINAC2 - dV/V Sensitivity

almost constant for $\Delta V/V = -0.12\% \sim +0.12\%$

at the end of LINAC2 for five dV/V changes

S-band Optimization-III

(top left) change of longitudinal phase space, (top right), change of projected relative energy spread, (bottom left) change of beam energy when RF amplitude of an RF station in S-band LINAC2 is changed by $\pm 0.12\%$ (= 0.04\% in rms) with five steps (step size = 0.06\%). please note that energy is almost constant even though dV/V is changed by $\pm 0.12\%$.

dE $\sim$ 1.92 MeV for dV/V = $\pm 0.12\%$
dE/E $\sim$ 0.03\% for dV/V = $\pm 0.12\%$
energy spread change $\sim$ 0.045\% for dV/V = $\pm 0.12\%$

In this case, XFEL wavelength change $\sim$ 0.06\%
S-band LINAC2 - Alignment Issues

When linac tubes are misaligned, emittance growth is a function of misalignment, β-function, charge, transverse wakefield, beam energy, the structure length $L$, and the structure frequency, and bunch length.

$$ W_\perp(z) \approx \frac{2Z_0cz}{\pi a^3 \sqrt{a^2 + 5z\lambda_{rf}}} \left(\text{V/C/m}^2\right); \text{ transverse wakefield, } Z_0 \approx 377 \Omega $$

$$ \frac{\varepsilon_0 + \Delta \varepsilon}{\varepsilon_0} \approx \sqrt{1 + \left(\frac{\pi r_e}{Z_0 c}\right)^2 \frac{N^2 \left(W_\perp\right)^2 L^2 \beta}{\varepsilon_n \gamma} \Delta x^2} $$

If all 68 S-band tubes in LINAC2 have a horizontal misalignment of 500 µm, beam horizontal centroid is slightly changed while change in the vertical centroid is ignorable. Generally, for the same linac length, transverse wakefield effect in S-band linac is weaker than that in C-band linac. But accumulated overall beam dilution due to the transverse short-range wakefield is larger than C-band based LINAC2 due to its much longer S-band linac.
When linac tubes are misaligned, emittance growth is a function of misalignment, $\beta$-function, charge, transverse wakefield, beam energy, the structure length $L$, and the structure frequency.

$$W_\perp(z) \approx \frac{2Z_0cz}{\pi a^3 \sqrt{a^2 + 5z\lambda_{rf}}} (V/C/m^2); \text{ transverse wakefield, } Z_0 \approx 377 \Omega$$

$$\frac{\varepsilon_0 + \Delta \varepsilon}{\varepsilon_0} \approx \sqrt{1 + \left( \frac{\pi r_e}{Z_0 c} \right)^2 \frac{N^2 \langle W_\perp \rangle^2 L^2 \beta}{\varepsilon_n \gamma} \Delta x^2}$$

Even though all 68 S-band tubes in LINAC2 have a horizontal misalignment of 500 $\mu$m, emittance growths due to the transverse short-range wakefield at the end of linac are small enough:

$\Delta \varepsilon_{nx} \sim 0.004 \mu$m, $\Delta \varepsilon_{ny} \sim 0.001 \mu$m

Therefore, S-band tubes can be aligned with the normal alignment technology.
SwissFEL Optimization-III with a longer S-band RF Linacs for Chirp Compensation

SwissFEL Optimization-VI with S-band & C-band RF Linacs for Chirp Compensation

Energy Chirp Control with C-band Linac

ASTRA up to exit of SB02 & ELEGANT from exit of SB02 to consider space charge, CSR, ISR, and wakefields!
C-band based LINAC2 after BC2

Length of one FODO cell in LINAC2
= four 2.0 m long PSI standard C-band tubes
+ two 0.5 m long PSI standard diagnostic sections
+ four 0.1 m long drifts for component assembly
+ two 0.25 m long QMs = 9.9 m

Pure active length per tube ~ 1.71578 m
Number of cell per tube = 91 including two coupler cells
Central cell length ~ 18.750 mm
Iris diameter ~ 14.6 mm
Total cells in LINAC2 = 24 FODO cells
No. of C-band tubes = CB01-CB96 for 24 FODO cells
Total needed C-band tubes = 96
Total needed RF stations = 48 with two tubes per RF station
Total needed QMs in LINAC2 = 2x24 = 48
Total length of LINAC2 = 237.6 m (116 m shorter than OPT-III)
Performance of C-band based LINAC2

Performance of Optimization-VI is exactly same as that of Optimization-III!

Optimization-VI
- LINAC2 phase = 10 deg
- Linac length = 540 m
- \(\sigma_u = 0.014\%\)

Optimization-VII
- LINAC2 phase = 9 deg
- Linac length = 510 m
- \(\sigma_u = 0.016\%\)

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Due to near on-crest operation at LINAC2, sensitivity of RF phase error becomes weaker!

116 m shorter than Optimization-III

Optimization - VI, \(\phi_{rf} \sim 10\) degree

\[\sigma_\delta \approx \left| \frac{(1 + 0.25i)9.55\varepsilon_0 N_r W_\parallel (1.3\sigma_z) - 2.35\sigma_z k_{rf} G \sin \phi_{rf}}{2.35G \cos \phi_{rf}} \right|\]

\[W_\parallel(z) \approx \frac{Z_0 c}{\pi a \sqrt{a^2 + 8z\lambda_{rf}}} (V/C/m); \text{long. wakefield}\]

\(\phi_{rf}\) giving minimum \(\sigma_\delta\) is determined when \(\text{Re}(\sigma_\delta) = 0\)

BC1                LINAC1           BC2                                            C-band LINAC2

degree 10~ VI on Optimization

Yujong Kim @ Idaho State University and Thomas Jefferson National Accelerator Facility, USA
Performance of C-band based LINAC2

\[ I_{\text{peak}} < 1.6 \text{kA for } |dz| < 20 \mu m \]

\[ \varepsilon_{n,\text{slic}} < 0.33 \mu m \text{ for } |dz| < 20 \mu m \]

\[ \sigma_{dE,\text{slic}} < 148 \text{ keV for whole bunch} \]
\[ \sigma_{dE,\text{slic}} < 30.0 \text{ keV for } |dz| < 20 \mu m \]

Slice Beam Parameters of Optimization-VI is exactly same as those of Optimization-III!

All slice parameters at FEL1, FEL2, and FEL3 are similar to these.
C-band LINAC2 - $\Delta\phi_{\text{rf}}$ Sensitivity

(looser phase tolerance due to near on-crest)

$\Delta\phi_{\text{rf}} = -1.2\ \text{deg}$

$\Delta\phi_{\text{rf}} = +1.2\ \text{deg}$

at the end of LINAC2 for five $\Delta\phi_{\text{rf}}$ changes

(C-band Optimization-VI)

small change of beam energy against $\Delta\phi_{\text{rf}}$! phase error sensitivity is lower due to near on-crest operation at C-band LINAC2.

5.3 MeV

1 ps

at the end of LINAC2 for five $\Delta\phi_{\text{rf}}$ changes

(top left) change of longitudinal phase space, (top right), change of projected relative energy spread, (bottom left) change of beam energy when RF phase of an RF station in C-band LINAC2 is changed by $\pm1.2\ \text{deg} (= 0.4\ \text{deg in rms})$ with five steps (step size = 0.6 deg). Please note that $\pm1.2\ \text{deg}$ in C-band RF system corresponding to about $\pm0.6\ \text{ps}$.

dE ~ 6.35 MeV for 1.2 ps, dE ~ 5.3 MeV for 1.0 ps
dE/E ~ 0.084% for $\Delta\phi_{\text{rf}} = 2.0\ \text{deg} (= 1\ \text{ps})$
energy spread change ~ 0.67% for $\Delta\phi_{\text{rf}} = 2.0\ \text{deg}$

In this case, XFEL wavelength change ~ 0.17%
C-band LINAC2 - dV/V Sensitivity

almost constant for ΔV/V = -0.12% ~ +0.12%

weaker nonlinearity in C-band: FEL BW is almost same as that of S-band

at the end of LINAC2 for five dV/V changes

(top left) change of longitudinal phase space, (top right), change of projected relative energy spread, (bottom left) change of beam energy when RF amplitude of an RF station in C-band LINAC2 is changed by ±0.12% (= 0.04% in rms) with five steps (step size = 0.06%). Please note that energy is almost constant even though dV/V is changed by ±0.12%.

dE ~ 2.06 MeV for dV/V = ±0.12%
dE/E ~ 0.033% for dV/V = ±0.12%
energy spread change ~ 0.001% for dV/V = ±0.12%

In this case, XFEL wavelength change ~ 0.066%
**C-band LINAC2 - Alignment Issues**

When linac tubes are misaligned, emittance growth is a function of misalignment, $\beta$-function, charge, transverse wakefield, beam energy, the structure length $L$, and the structure frequency.

$$W_\perp(z) \approx \frac{2Z_0cz}{\pi a^3 \sqrt{a^2 + 5z\lambda_{rf}}} (V/C/m^2); \text{ transverse wakefield, } Z_0 \approx 377 \Omega$$

$$\frac{\varepsilon_0 + \Delta \varepsilon}{\varepsilon_0} \approx \sqrt{1 + \left(\frac{\pi r_e}{Z_0 c}\right)^2 \frac{N^2 \left\langle W_\perp \right\rangle^2 L^2 \beta}{\varepsilon_n \gamma}\Delta x^2}$$

If all 96 C-band tubes in LINAC2 have a horizontal misalignment of 500 µm, beam horizontal centroid is slightly changed while change in the vertical centroid is ignorable. Generally, for the same linac length, transverse wakefield effect in C-band linac is stronger than that in S-band linac. But accumulated overall beam dilution due to the transverse short-range wakefield is smaller than S-band based LINAC2 due to its much shorter C-band linac.
When linac tubes are misaligned, emittance growth is a function of misalignment, β-function, charge, transverse wakefield, beam energy, the structure length $L$, and the structure frequency.

$$W_{\perp}(z) \approx \frac{2Z_0cz}{\pi a^3 \sqrt{a^2 + 5z\lambda_{rf}}} (V/C/m^2); \text{ transverse wakefield, } Z_0 \approx 377 \Omega$$

$$\frac{\varepsilon_0 + \Delta\varepsilon}{\varepsilon_0} \approx \sqrt{1 + \left(\frac{\pi r_e}{Z_0c}\right)^2 \frac{N^2 \langle W_{\perp}\rangle^2 L^2 \beta}{\varepsilon_n \gamma} \Delta x^2}$$

Even though all 96 C-band tubes in LINAC2 have a horizontal misalignment of 500 µm, emittance growths due to the transverse short-range wakefield at the end of linac are ignorable:

$\Delta\varepsilon_{nx} \sim 0.001 \mu m, \Delta\varepsilon_{ny} \sim 0.000 \mu m$

Therefore, C-band tubes can be aligned with the normal alignment technology.
Energy Chirp Control with X-band Linac

SwissFEL Optimization-III with a longer S-band RF Linacs for Chirp Compensation

ASTRA up to exit of SB02 & ELEGANT from exit of SB02 to consider space charge, CSR, ISR, and wakefields.

SwissFEL Optimization-XIX with S-band & X-band RF Linacs for Chirp Compensation

Yujong Kim @ Idaho State University and Thomas Jefferson National Accelerator Facility, USA
**X-band based LINAC2 after BC2**

**LINAC2 for Optimization-XIX**

QF: 0.965 m long Three X-band Tubes
- 0.1 m long drift
  - 11992 MHz
  - 40 MV/m with 29 MW

QD: 0.965 m long Three X-band Tubes
- 0.5 m long diagnostic section
- 0.1 m long drift
  - 11992 MHz
  - 40 MV/m with 29 MW

0.25 m long QM

**One FODO Cell for LINAC2 = 7.89 m**

**Optics for X-band Based LINAC2**

- $\beta_x$
- $\beta_y$
- $\gamma_x$

**length of one FODO cell in LINAC2**
- six 0.965 m long PSI standard X-band tubes
- + two 0.5 m diagnostic sections
- + six 0.1 m long drifts
- + two 0.25 m long QMs = 7.89 m
- pure active length per tube ~ 749.5544 mm
- number of cell per tube = 72 including two coupler cells
- central /coupler cell length ~ 10.4104 mm / 10.4132 mm
- average iris diameter ~ 9.0969 mm
- flange length = 107.7228 mm
- total tube length with two flanges = 965 mm
- total cells in LINAC2 = 26 for $\Delta E \sim 4600$ MeV
- No. of X-band tubes = XB01-XB156 for 26 FODO cells
- total needed X-band tubes = 156
- total needed RF stations = 26 with six tubes per RF station
- total needed QMs in LINAC2 = 2x26 = 52
- total length of LINAC2 = 205.14 m (148.46 m shorter than OPT-III)
Performance of X-band based LINAC2

Performance of Optimization-XIX is exactly same as that of Optimization-III!

\[ \sigma_\delta \approx \frac{(1 + 0.25i)9.55\varepsilon_0 N r_f W(1.3\sigma_z) - 2.35\sigma_z k_{rf} G \sin \phi_{rf}}{2.35G \cos \phi_{rf}} \]

\[ W(z) \approx \frac{Z_0c}{\pi a \sqrt{a^2 + 8z\lambda_{rf}}} \text{ (V/C/m); long. wakefield} \]

\[ \phi_{rf} \text{ giving minimum } \sigma_\delta \text{ is determined when } \text{Re}(\sigma_\delta) = 0 \]

Optimization - XIX, \( \phi_{rf} \approx -5 \text{ degree} \)

due to near on-crest operation at LINAC2, sensitivity of RF phase error becomes weaker!

149 m shorter than Optimization-III

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Performance of X-band based LINAC2

Slice Beam Parameters of Optimization-XIX is almost same as those of Optimization-III!

Slice emittance-μm for |dz| < 20 μm

all slice parameters at FEL1 FEL2, and FEL3 are similar to these.
C-band & X-band LINAC2 - $\Delta \phi_{\text{rf}}$ Sensitivity

C-band based LINAC2

$\Delta \phi_{\text{rf}} = -1.2 \text{ deg}$

$\Delta \phi_{\text{rf}} = +1.2 \text{ deg}$

±1.2 deg in C-band = ± 0.6 ps

at the end of LINAC2 for five $\Delta \phi_{\text{rf}}$ changes

X-band based LINAC2

$\Delta \phi_{\text{rf}} = +1.2 \text{ deg}$

$\Delta \phi_{\text{rf}} = -1.2 \text{ deg}$

±1.2 deg in X-band = ± 0.3 ps

at the end of LINAC2 for five $\Delta \phi_{\text{rf}}$ changes

C-band Optimization-VI

dE ~ 3.6 MeV for 0.6 ps, dE ~ 5.9 MeV for 1.0 ps
dE/E ~ 0.092% for $\Delta \phi_{\text{rf}} = 4.0 \text{ deg}$ (= 1 ps)

In this case, XFEL wavelength change ~ 0.18%

X-band Optimization-XIX

dE ~ 5.3 MeV

1 ps

at the end of LINAC2 for five $\Delta \phi_{\text{rf}}$ changes

0.5 ps

2.95 MeV

Yujong Kim @ Idaho State University and Thomas Jefferson National Accelerator Facility, USA
C-band and X-band LINAC2 - dV/V Sensitivity

Almost constant for $\Delta V/V = -0.12\% ~ +0.12\%$

at the end of LINAC2 for five dV/V changes

C-band Optimization-VI

X-band Optimization-XIX

Almost constant for $\Delta V/V = -0.12\% ~ +0.12\%$

stronger nonlinearity in X-band:
XFEL BW ~ 44% larger than C-band & S-band

Similar to C-band but the power gain of X-band SLED-II is about 2 times high.
More fine voltage control is needed in modulators for X-band.

Yujong Kim @ Idaho State University and Thomas Jefferson National Accelerator Facility, USA
When linac tubes are misaligned, emittance growth is a function of misalignment, $\beta$-function, charge, transverse wakefield, beam energy, the structure length $L$, and the structure frequency. The wakefield was controlled by choosing smaller $\beta$-function.

$$ W_\perp(z) \approx \frac{2Z_0cz}{\pi a^3 \sqrt{a^2 + 5z\lambda_{rf}}} (V/C/m^2); \text{ transverse wakefield, } Z_0 \approx 377 \Omega $$

If all 156 X-band tubes in LINAC2 have a horizontal misalignment of 500 $\mu$m, beam horizontal centroid is slightly changed while change in the vertical centroid is ignorable. Generally, for the same linac length, transverse wakefield effect in X-band linac is stronger than that in S-band linac. But accumulated overall beam dilution due to the transverse short-range wakefield in X-band linac can be controllable by choosing smaller $\beta$-function and shorter X-band linac.
X-band LINAC2 Alignment Issues

When linac tubes are misaligned, emittance growth is a function of misalignment, β-function, charge, transverse wakefield, beam energy, the structure length \(L\), and the structure frequency. The wakefield was controlled by choosing smaller β-function.

\[
W_\perp(z) \approx \frac{2Z_0cz}{\pi a^3 \sqrt{a^2 + 5z\lambda_{rf}}} (V/C/m^2); \text{ transverse wakefield, } Z_0 \approx 377 \Omega
\]

\[
\frac{\varepsilon_0 + \Delta\varepsilon}{\varepsilon_0} \approx \sqrt{1 + \left(\frac{\pi r_e}{Z_0 c}\right)^2 \frac{N^2 \langle W_\perp \rangle L^2 \beta}{\varepsilon_n \gamma} \Delta x^2}
\]

Even though all 156 X-band tubes in LINAC2 have a horizontal misalignment of 500 µm, emittance growths due to the transverse short-range wakefield at the end of linac are ignorable:

\(\Delta\varepsilon_{nx} \sim 0.005 \mu m, \Delta\varepsilon_{ny} \sim 0.000 \mu m\)

Therefore, X-band tubes can be aligned with the normal alignment technology.
Several Directions for Stable Compact XFELs

- Reduce overall bunch compression factor by choosing a high gradient gun, by choosing a shorter bunch length at gun, and by choosing a lower peak current at undulator. These make all things easier (wakefields, CSR, RF jitter, and so on).

- Reduce RF jitter tolerances and transverse wakefield in front of BC1 by choosing a lower RF frequency linac (ex, S-band), which is also helpful to install a higher harmonic RF cavity (ex, X-band) to linearize the longitudinal phase space for BC operations. If you are rich, avoid a higher frequency RF linac between BC1 and BC2 too to reduce the nonlinearity in longitudinal phase space and to improve XFEL photon bandwidth.

- Avoid using any SLED in front of BC1 (also BC2 if you are rich) to reduce RF jitter tolerances.

- To relax RF jitter tolerances, choose somewhat lower gradients and the near on-crest RF phases by optimizing energy chirping and BCs.
Several Directions - continued

☐ To relax RF jitter tolerances, if it is possible, use many RF stations and avoid too high power gain from the X-band SLED-II after BC2.
Summary

☐ We can control energy chirp effectively even at compact XFEL facilities by optimizing RF gradient, RF phase, and RF frequency, and linac length.

☐ In case of C-band and X-band linacs, RF phase jitter tolerance can be reduced by operating near on-crest RF phase.

☐ C-band and X-band can supply similar performance of that S-band (or much effective) if we consider energy chirp, XFEL bandwidth, and linac length.

☐ But X-band linac supplies a somewhat worse nonlinearity in the longitudinal phase space and a somewhat bigger energy spread and XFEL photon beam bandwidth than those of C-band based linac.

☐ In case of X-band, further optimizations on linac structure geometry, power gain in SLED-II, hardware cost, RF gradient, RF phase, and reachable RF tolerances are required to realize compact, stable, and high performance X-band based XFEL facilities.

☐ We may find a better solution in X-band based linac by using several recommended directions (see previous pages).
Single Spike with 10 pC - CSR Orbit Kicking

Under RF jitter tolerances, random RF jitters generates random CSR orbit kicking in the horizontal plan. There is no good way to compensate it because the CSR orbit kicking is random. Since its rms orbit fluctuation is larger than 100% of electron rms beamsize in undulator, there is a big impact on FEL lasing.

300 S2E simulations with RF Jitter Tolerances:

- change error ≤ 1% (rms)
- laser arrival timing error ≤ 20 fs (rms)
- injector S-band RF phase error ≤ 0.04 deg (rms)
- injector S-band RF voltage error ≤ 0.04% (rms)
- injector X-band RF phase error ≤ 0.16 deg (rms)
- injector X-band RF voltage error ≤ 0.16% (rms)
- BC power supply error ≤ 10 ppm (rms)

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Nominal Mode with 10 pC - CSR Orbit Kicking

Under same RF jitter tolerances for the single spike mode with 10 pC, we checked status of CSR kicking for the nominal mode with 10 pC. Clearly, its CSR orbit kicking is ignorable during the nominal mode, and lasing will be OK.

\[ \langle x \rangle \approx 8.5 \mu m \]

Can we get stable lasing?, certainly, good lasing.

300 S2E simulations with Required Tolerances:

- Change error \( \leq 1\% \) (rms)
- Laser arrival timing error \( \leq 1 \) fs (rms)
- Injector S-band RF phase error \( \leq 0.005 \) deg (rms)
- Injector S-band RF voltage error \( \leq 0.005\% \) (rms)
- Injector X-band RF phase error \( \leq 0.005\) deg (rms)
- Injector X-band RF voltage error \( \leq 0.025\% \) (rms)
- BC power supply error \( \leq 7.5 \) ppm (rms)

Median : \( \sim 2.5 \) GW (80% core slices)

RMS variation : \( \sim 5\% \)

Very stable saturation power!
Other Difficulty Example - SwissFEL Injector

Q ~ 100 pC
gun gradient ~ 100 MV/m
1% gun gradient error

See pages 90-91 for detailed injector layout and parameters
Q ~ 100 pC
gun RF phase ~ 37.89 deg
Other Difficulty Example - SwissFEL Injector

Q ~ 100 pC
main gun solenoid field ~ 0.206 T
1% solenoid field error = 0.00206 T = 20.6 Gauss
needed power supply dI/I ~ 10 ppm (rms)
misalignment of solenoid ~ 20 µm (0-to-max) giving $\Delta \epsilon_n = 1\%$

Yujong Kim @ Idaho State University and Thomas Jefferson National Accelerator Facility, USA
Wakefield of Two C-band Linac Structures

**MHI $2\pi/3$ Mode C-band Structure**
- average inner radius $a = 6.9535$ mm
- average outer radius $b = 20.10075$ mm
- period $p = 16.6667$ mm
- iris thickness $t = 2.5$ mm
- cell number for 2 m structure = 119
- attenuation constant $\tau = 0.452$
- average shunt impedance = 69.5 M$\Omega$/m
- filling time = 222 ns
- RF pulse length = 0.5 $\mu$s
- required RF power for 28 MV/m = 38 MW
- one 50 MW klystron can drive 3 structures

This structure is used for linac Optimization-XIV and Optimization-XV with RF Option-IV.

**PSI $3\pi/4$ Mode C-band Structure**
- average inner radius $a = 6.9545$ mm
- average outer radius $b = 20.7555$ mm
- period $p = 18.7501$ mm
- iris thickness $t = 4.0$ mm
- cell number for 2 m structure = 106
- attenuation constant $\tau = 0.630$
- average shunt impedance = 66.1 M$\Omega$/m
- filling time = 333 ns
- RF pulse length = 0.5 $\mu$s
- required RF power for 26 MV/m = 28.5 MW
- required RF power for 28 MV/m = 33 MW
- one 50 MW klystron can drive 4 structures

This structure is used for linac Optimization-XVII, and Optimization-XVIII with RF Option-VII, VIII.

Disk loaded type linac structure

Wakefield of Two C-band Linac Structures

**MHI $2\pi/3$ Mode C-band Structure**
- average inner radius $a = 6.9535$ mm
- average outer radius $b = 20.10075$ mm
- period $p = 16.6667$ mm
- iris thickness $t = 2.5$ mm
- cell number for 2 m structure = 119
- attenuation constant $\tau = 0.452$
- average shunt impedance = 69.5 M$\Omega$/m
- filling time = 222 ns
- RF pulse length = 0.5 $\mu$s
- required RF power for 28 MV/m = 38 MW
- one 50 MW klystron can drive 3 structures

This structure is used for linac Optimization-XIV and Optimization-XV with RF Option-IV.

**PSI $3\pi/4$ Mode C-band Structure**
- average inner radius $a = 6.9545$ mm
- average outer radius $b = 20.7555$ mm
- period $p = 18.7501$ mm
- iris thickness $t = 4.0$ mm
- cell number for 2 m structure = 106
- attenuation constant $\tau = 0.630$
- average shunt impedance = 66.1 M$\Omega$/m
- filling time = 333 ns
- RF pulse length = 0.5 $\mu$s
- required RF power for 26 MV/m = 28.5 MW
- required RF power for 28 MV/m = 33 MW
- one 50 MW klystron can drive 4 structures

This structure is used for linac Optimization-XVII, and Optimization-XVIII with RF Option-VII, VIII.

Disk loaded type linac structure
**Short-Range Wakefields of Two C-band Structures**

**MHI $2\pi/3$ Mode C-band Structure** *(red lines in plots below)*
This structure is used for SwissFEL linac Optimization-XIV and Optimization-XV with RF Option-IV.

**PSI $3\pi/4$ Mode C-band Structure** *(black lines in plots below)*
This structure is used for SwissFEL linac Optimization-XVII, and Optimization-XVIII with RF Option-VII or RF Option-VIII.

*both structures have almost same short-range wakefields!*
SwissFEL - Best Optimization with C-band LINAC1 & 2

Optimization-XVII with PSI C-band RF Structures for 1.6 kA

Optimization-XVIII with PSI C-band RF Structures for 2.7 kA

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