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

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  - Short-Range Wakefields
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- C-band based XFEL Driving Linac
- X-band based XFEL Driving Linac
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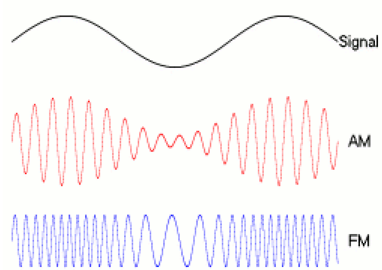
Acceleration - Traveling Wave (TW) Accelerator

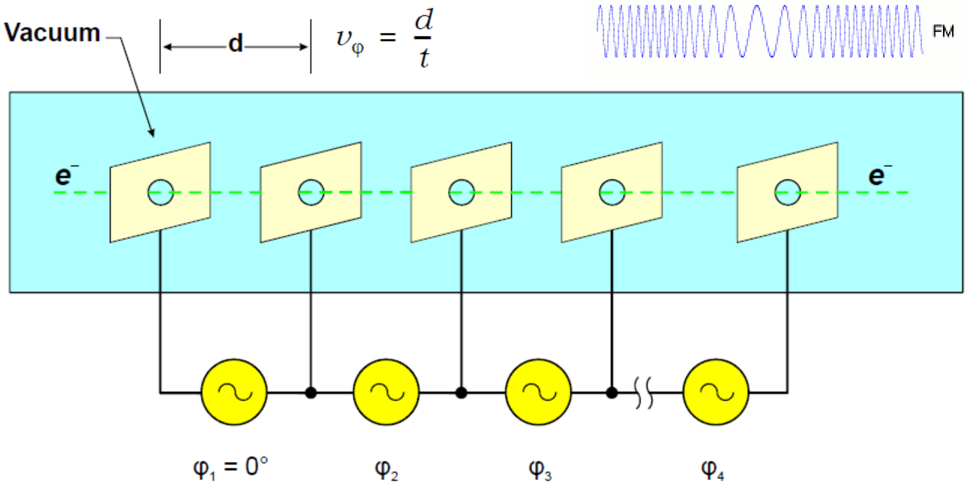
To avoid any arc between two electrodes, and to get a much higher beam energy gain, we use an Alternating Current (AC) type accelerator → RF Accelerator.

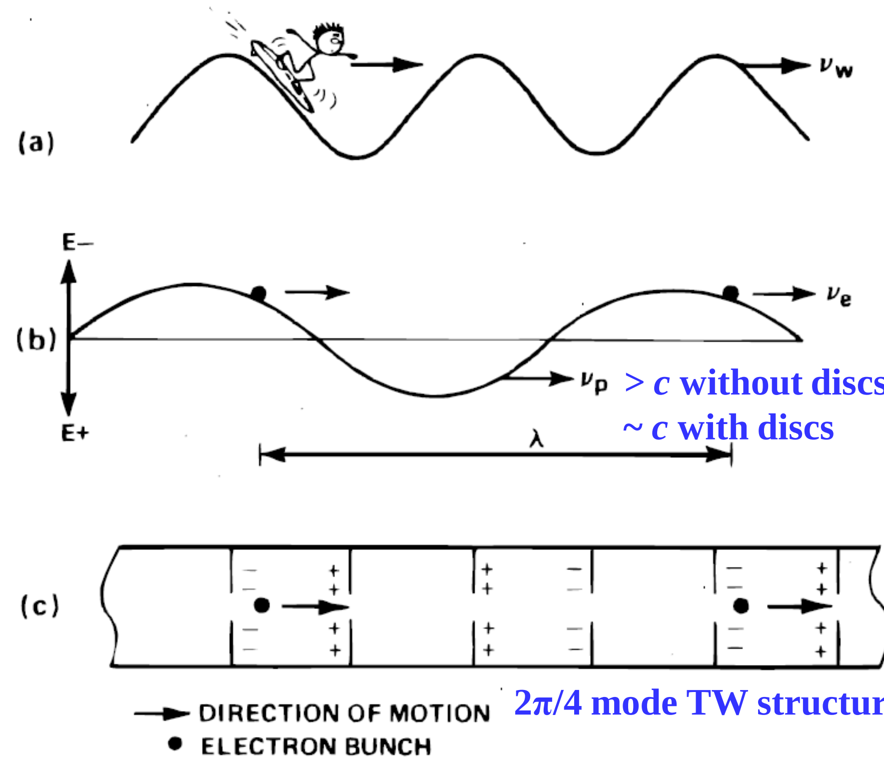
To get the best acceleration, we need a good synchronization between charged beams and RF wave (phase velocity of electromagnetic wave = velocity of electron beams).

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

VARIAN medical systems







2π/4 mode TW structure

RF Frequency, Microwave / Radar Bands

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.

Frequency Range	Microwave / Radar Bands
216 — 450 MHz	P-Band
1 — 2 GHz	L-Band
2 — 4 GHz	S-Band
4 — 8 GHz	C-Band
8 — 12 GHz	X-Band
12 — 18 GHz	K_u-Band
18 — 26.5 GHz	K-Band
26.5 — 40 GHz	K_a-Band
30 — 50 GHz	Q-Band
40 — 60 GHz	U-Band
50 — 75 GHz	V-Band
60 — 90 GHz	E-Band
75 — 110 GHz	W-Band
90 — 140 GHz	F-Band
110 — 170 GHz	D-Band
110 — 300 GHz	mm-Band

Bands for RF Accelerators

IEEE US Bands

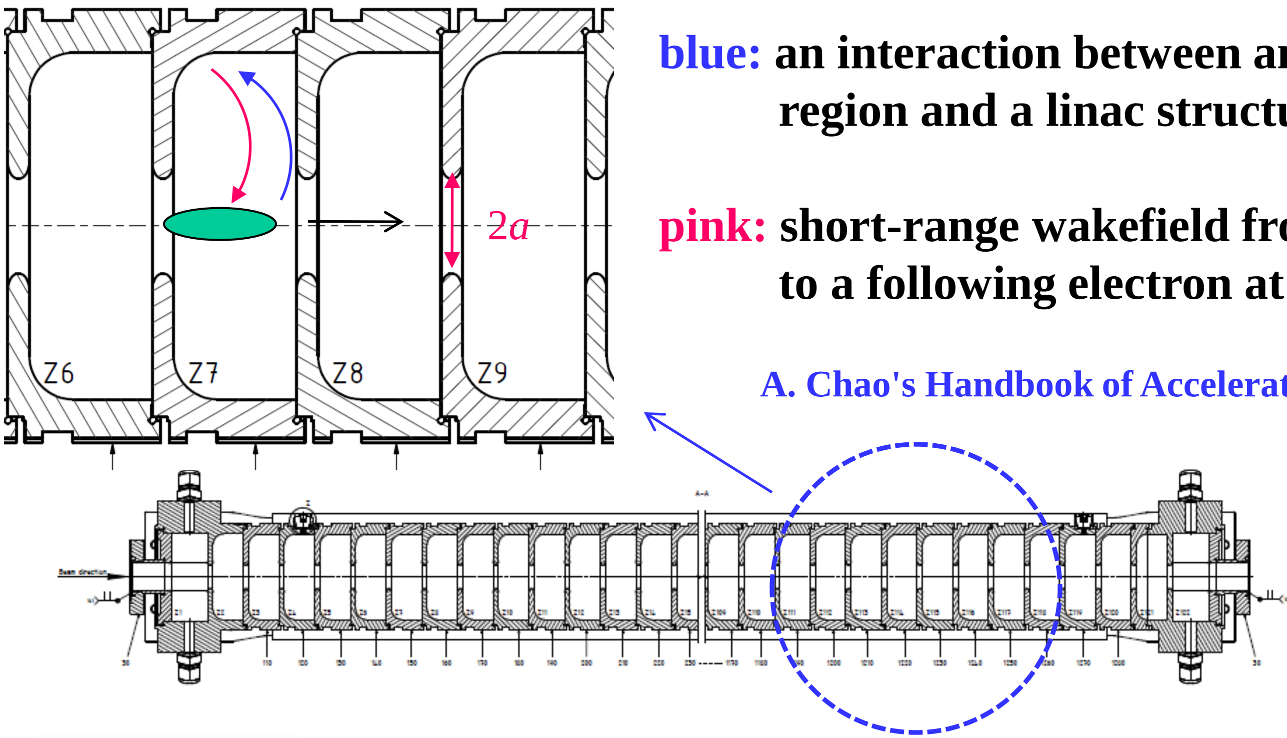
30 - 300 kHz : LF-band
300 - 3000 kHz : MF-band
3 - 30 MHz : HF-band
30 - 300 MHz : VHF-band
300 - 1000 MHz : UHF-band

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.

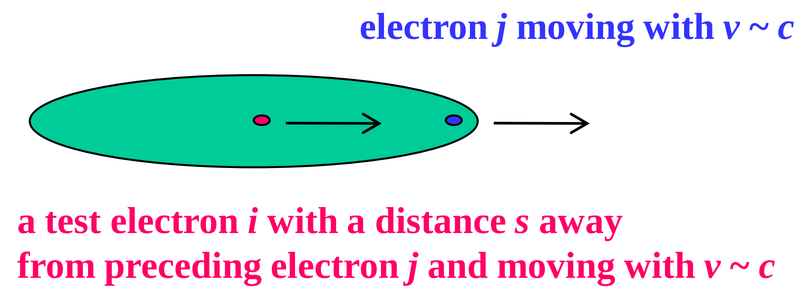
pink: short-range wakefield from the linac structure to a following electron at the tail region.

A. Chao's Handbook of Accelerator Physics & Engineering, p. 252
SLAC-AP-103 (LIAR manual)

Short-Range Wakefields in Linac Accelerators

Energy loss δE_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.

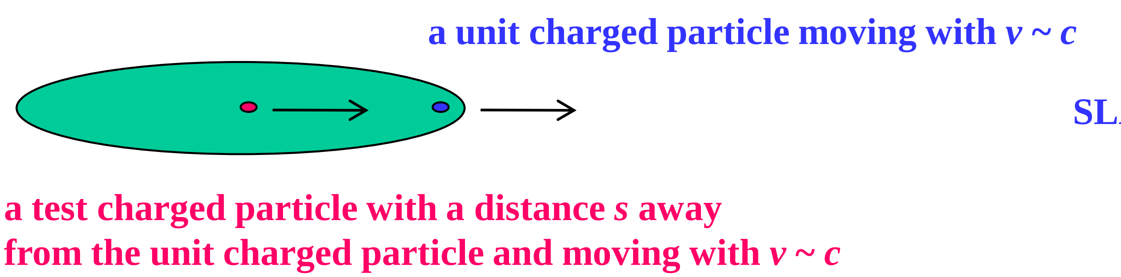
SLAC-AP-103 (LIAR manual)

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 λ_z, the bunch wake $\mathcal{W}(s)$ (= voltage gain for the test particle at position s) is given by

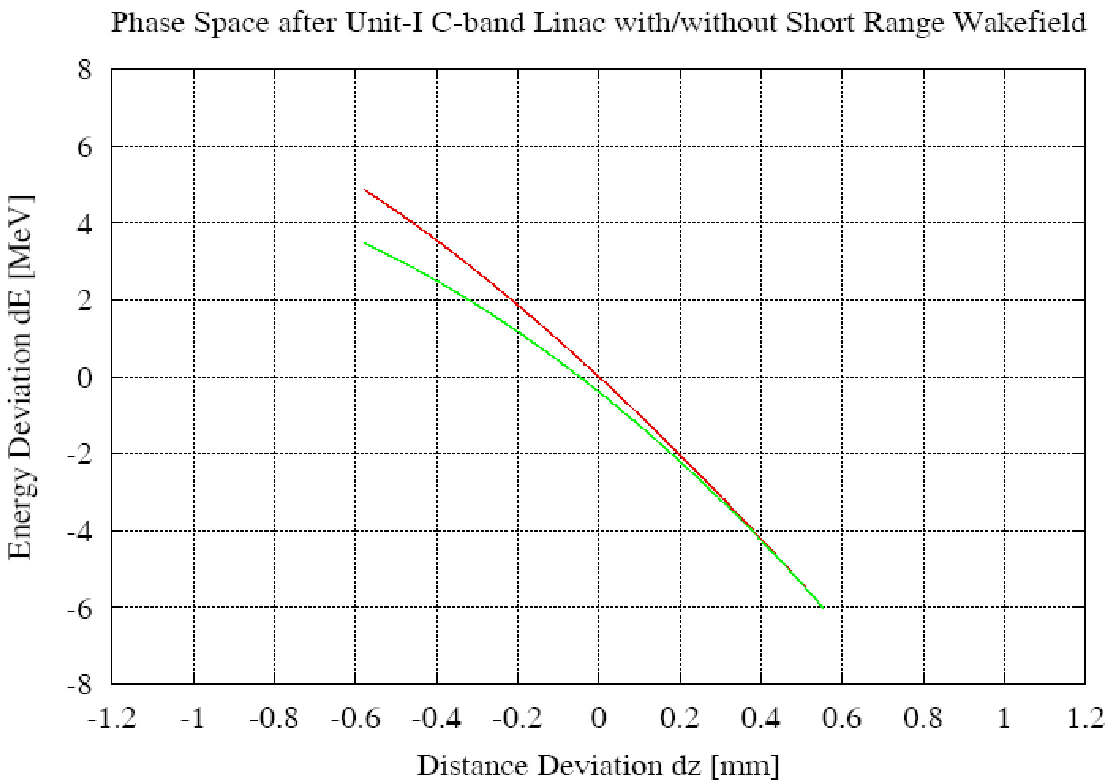
$$\mathcal{W}(s) = -\int_0^\infty W_L(s')\lambda_z(s-s')\,ds'$$

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.



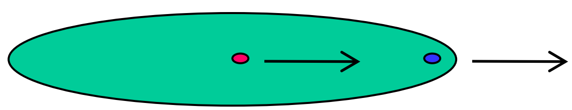
SLAC-AP-103 (LIAR manual)
SLAC-PUB-11829
SLAC-PUB-9798
TESLA Report 2004-01
TESLA Report 2003-19

Longitudinal Short-Range Wakefields



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 $v \sim c$

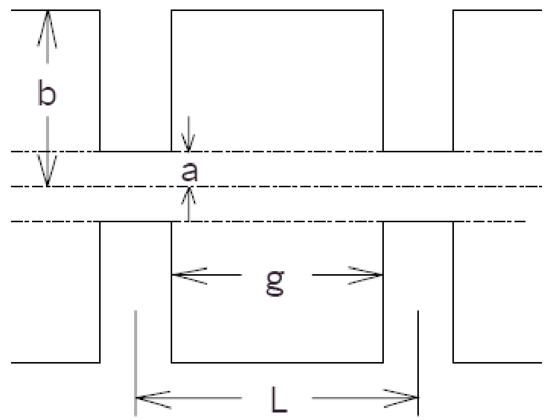
SLAC-AP-103 (LIAR manual)
SLAC-PUB-11829
SLAC-PUB-9798
TESLA Report 2004-01
TESLA Report 2003-19

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:



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

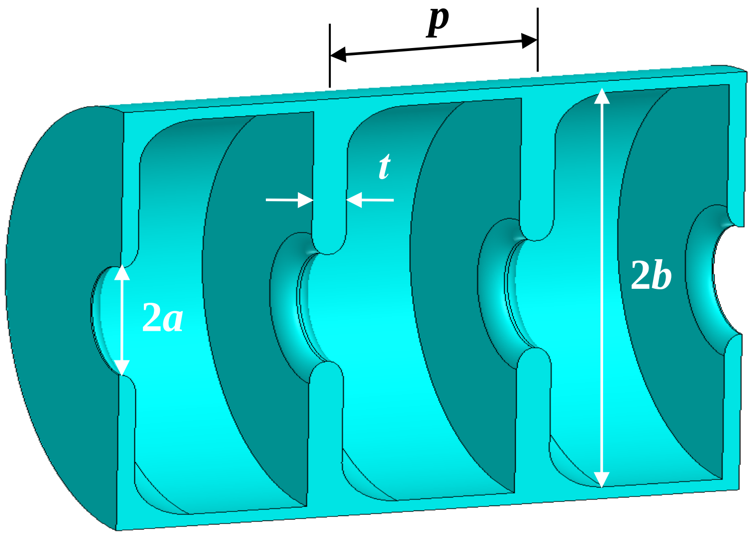
$$W_T(s) = \frac{cZ_0}{\pi a^4}s\left[2 + W_{T1}\sqrt{\zeta} + W_{T2}\zeta + W_{T3}\zeta\sqrt{\zeta}\right]$$

$$W_{L1} = -1.614r^{0.122}, \quad W_{L2} = +1.012r^{0.169}, \quad W_{L3} = -0.231r^{0.111}$$

$$W_{T1} = -2.781r^{0.217}, \quad W_{T2} = +1.637r^{0.511}, \quad W_{T3} = -0.364r^{0.793}$$

$$\zeta = \frac{Ls}{a^2} \qquad r = \frac{a/\lambda}{0.15}.$$

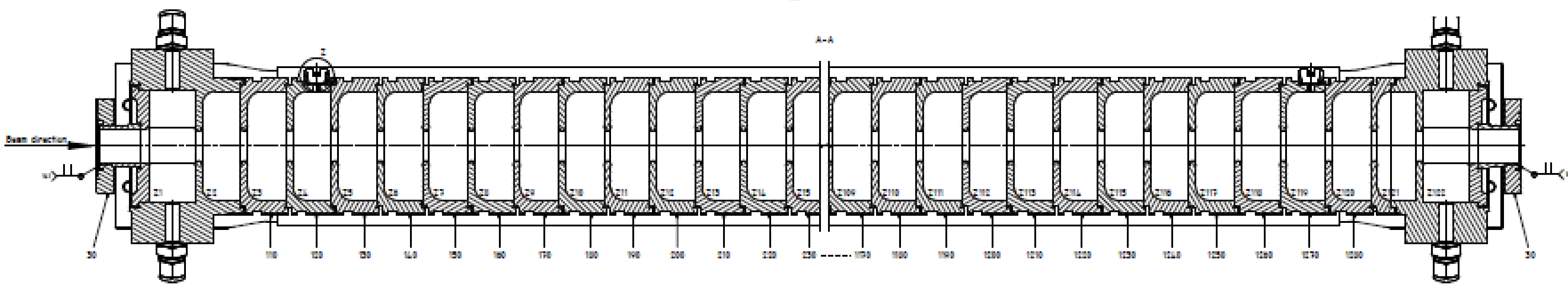
PSI S-band Linac Structure



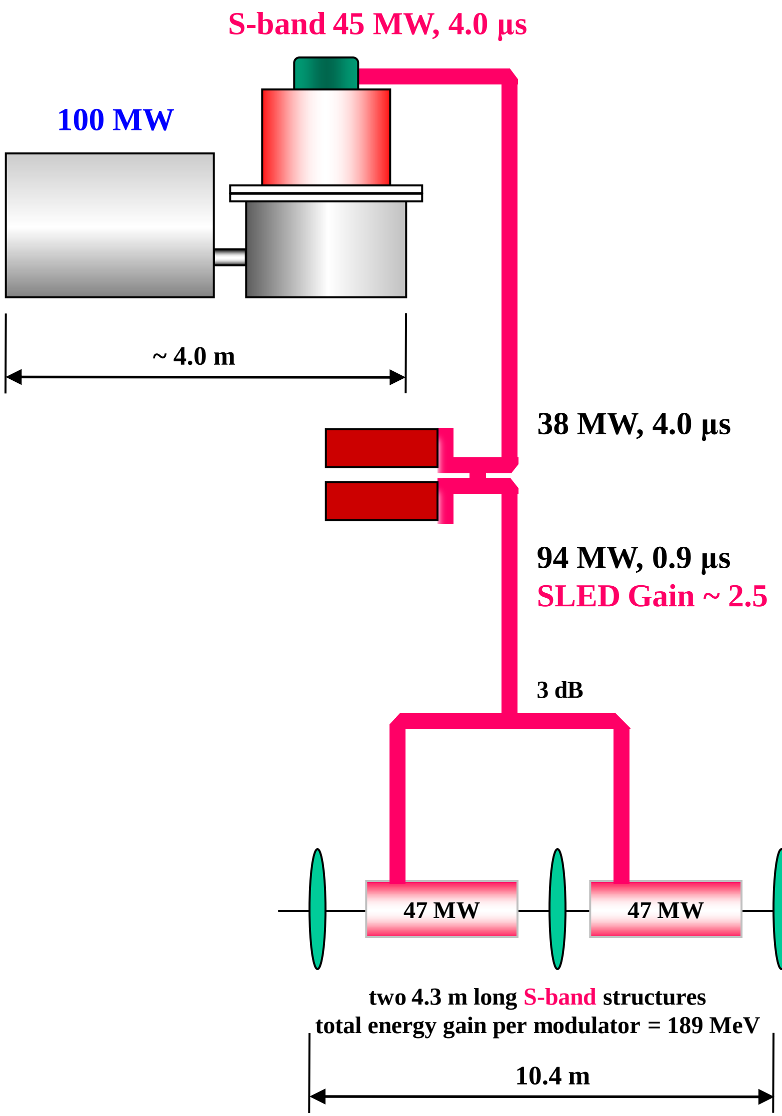
PSI disk loaded type S-band linac

PSI 4.3 m long 2π/3 S-band TW Structure

RF Frequency = 2997.924 MHz
average inner diameter 2*a* = 22.005 mm
average outer diameter 2*b* = 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

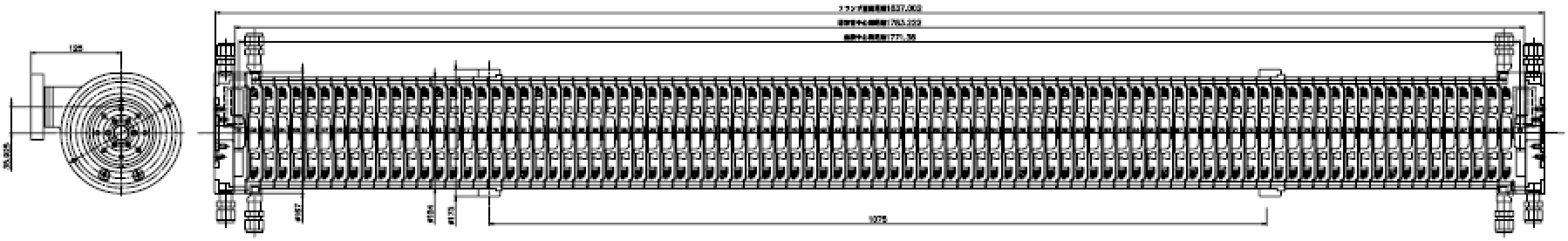


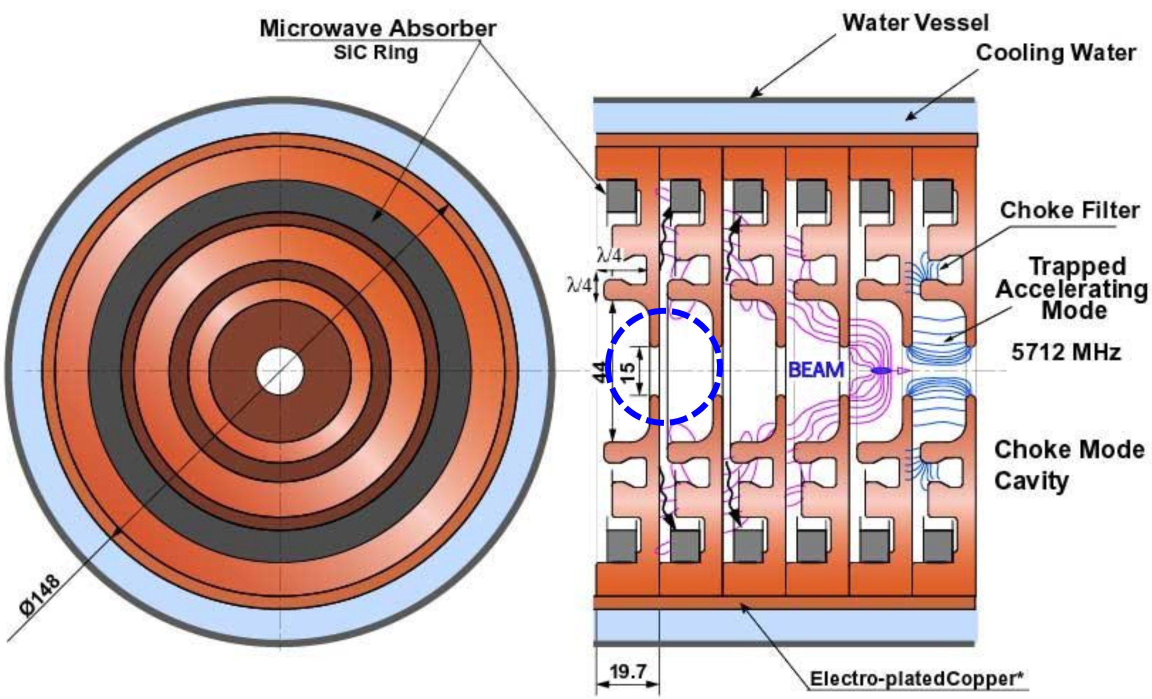
To drive two 4.3 m long S-band Structures

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
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

C-band TW RF Linac

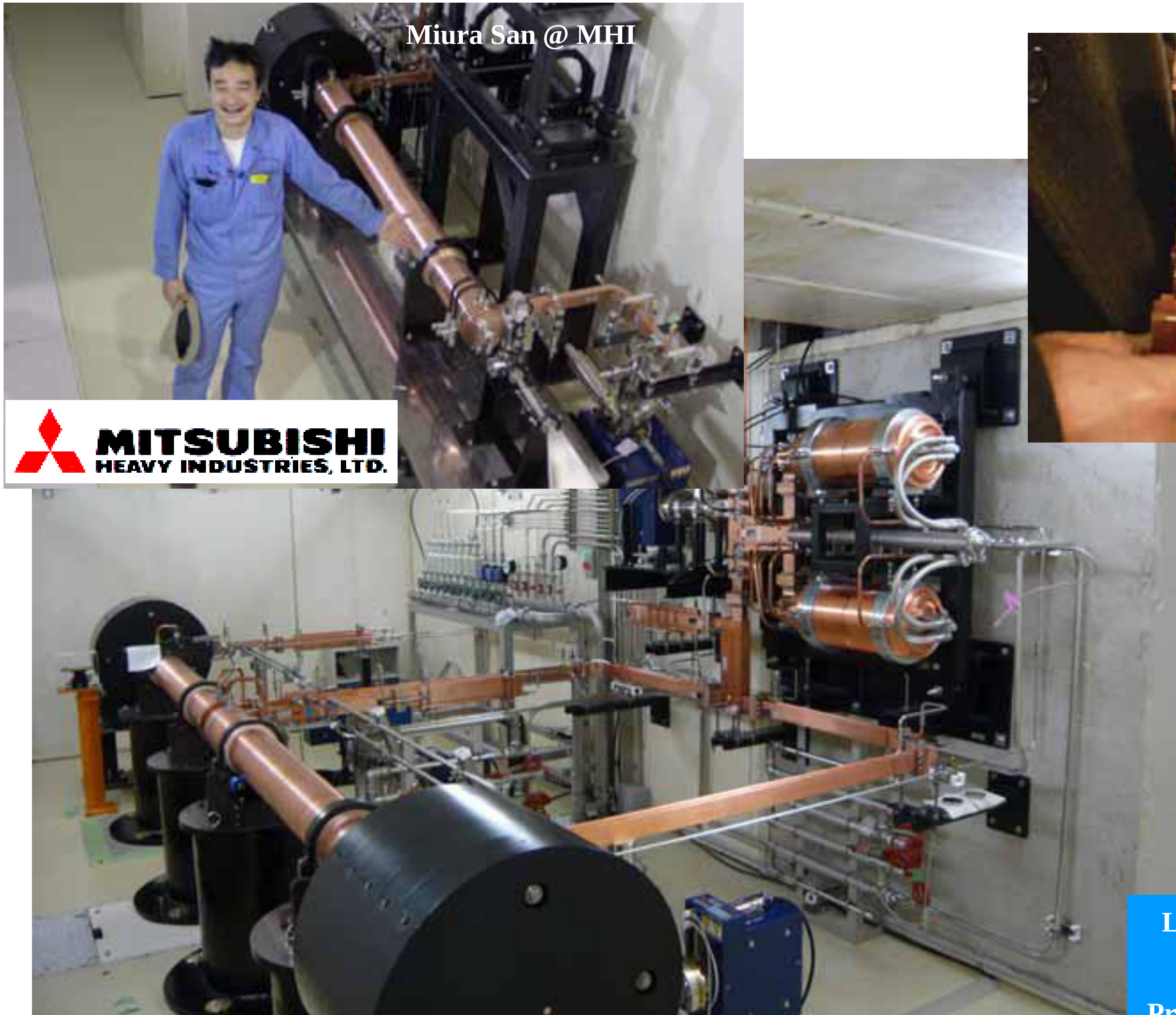




Frequency	5712 MHz
Phase shift per cell	3π/4
Field distribution	semi C.G.
Number of cells	91 cell
Active length	1791 mm
Iris aperture (2a) : up-stream : down-stream	17.4 mm 12.5 mm
Cavity diameter : up-stream : down-stream	45.3 mm 43.3 mm
Disk thickness: t	3.0 mm
Quality factor: Q	10.7-1 0.3 $\times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

$2a$ ~ 14 mm for SCSS structure
$2b$ ~ 40 mm
period p ~ 16.7 mm, t ~ 2.5 mm

C-band TW RF Linac



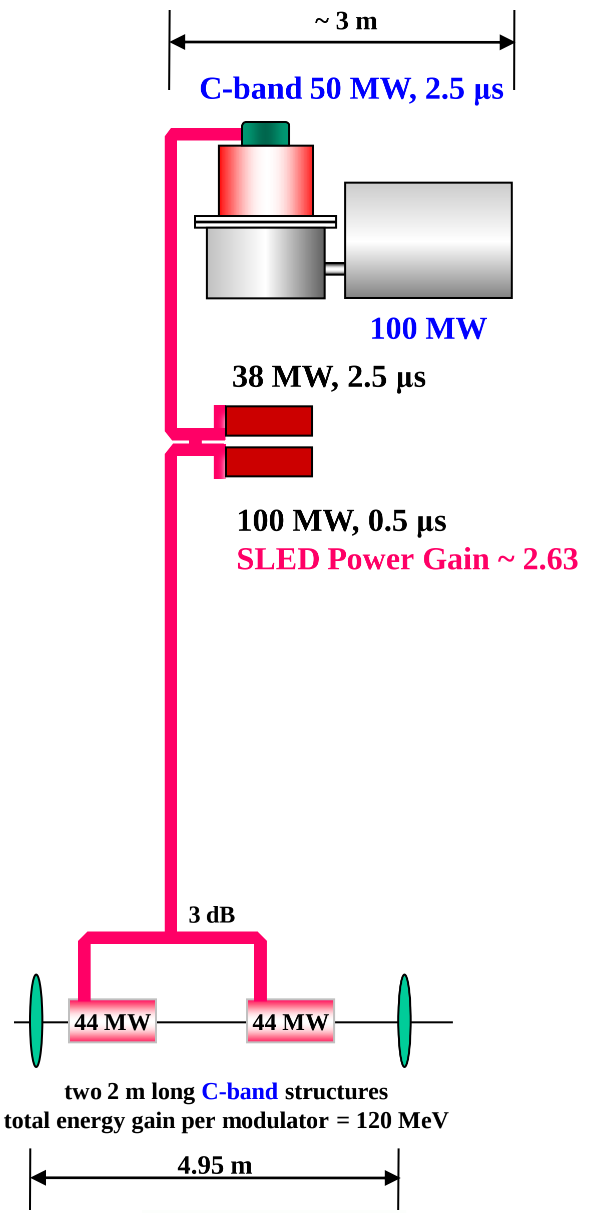
Miura San @ MHI

Let's thank to C-band RF Pioneers

Prof. H. Matsumoto of KEK
Prof. T. Shintake of RIKEN/SPring-8

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

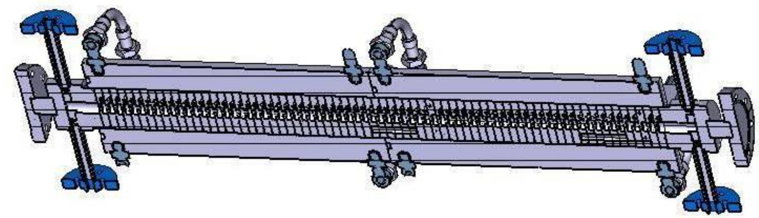
sensitivity of modulator error = low due to low SLED gain and many RF stations.

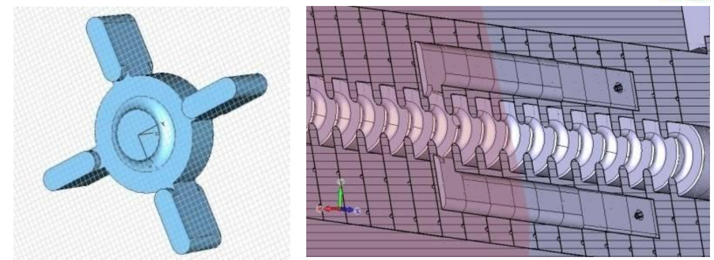
X-band TW Linac for SwissFEL

X-band Linac Structure with Alignemnt Monitor

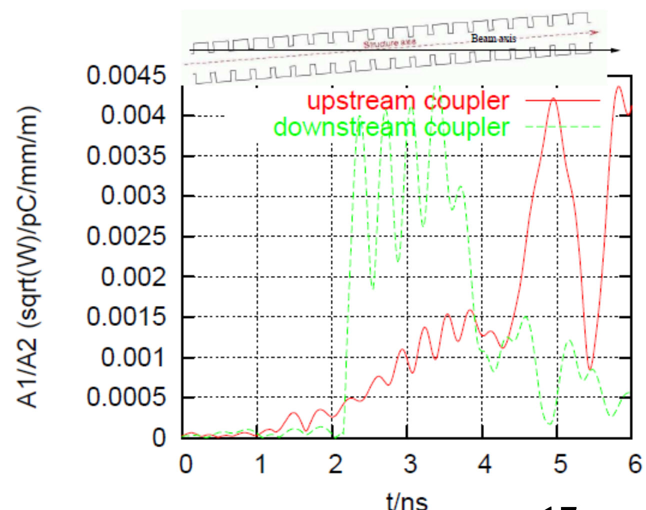
- developed with collaboration with CERN, ELETTRA & PSI
- original model: SLAC H75 type.
- resonance frequency: ~ 11991.648 MHz
- phase advance: 5π/6
- cell number: 72
- active length: 750 mm
- average iris diameter 2*a*: 9.1 mm
- average outer diameter 2*b*: 21.4267 mm
- cell length *p*: 10.4104 mm
- 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 ≤ 5 μm (rms)
- available signals : tilt, bend, offset, cell-to-cell misalignment

Courtesy of M. Dehler



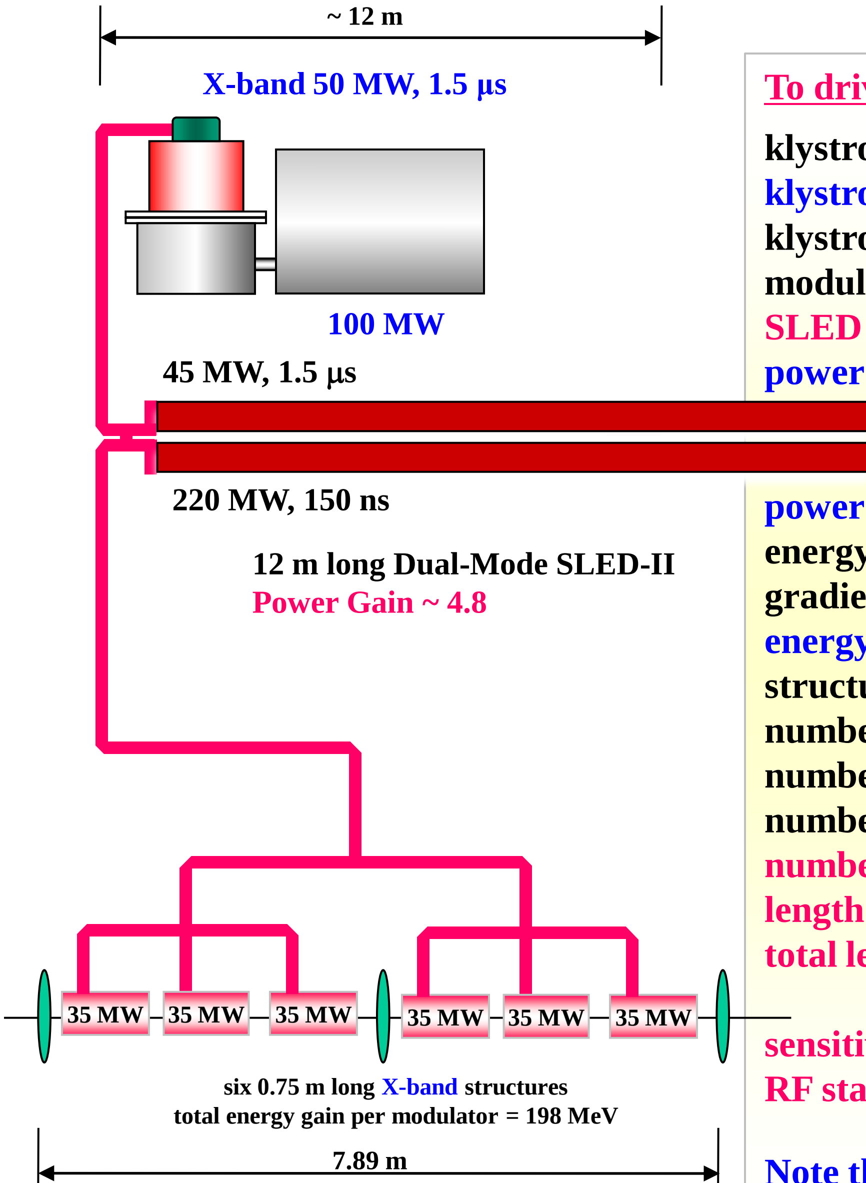


63th cell with radial coupling waveguides



RF Option for X-band TW RF Linac

Idaho Accelerator Center



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

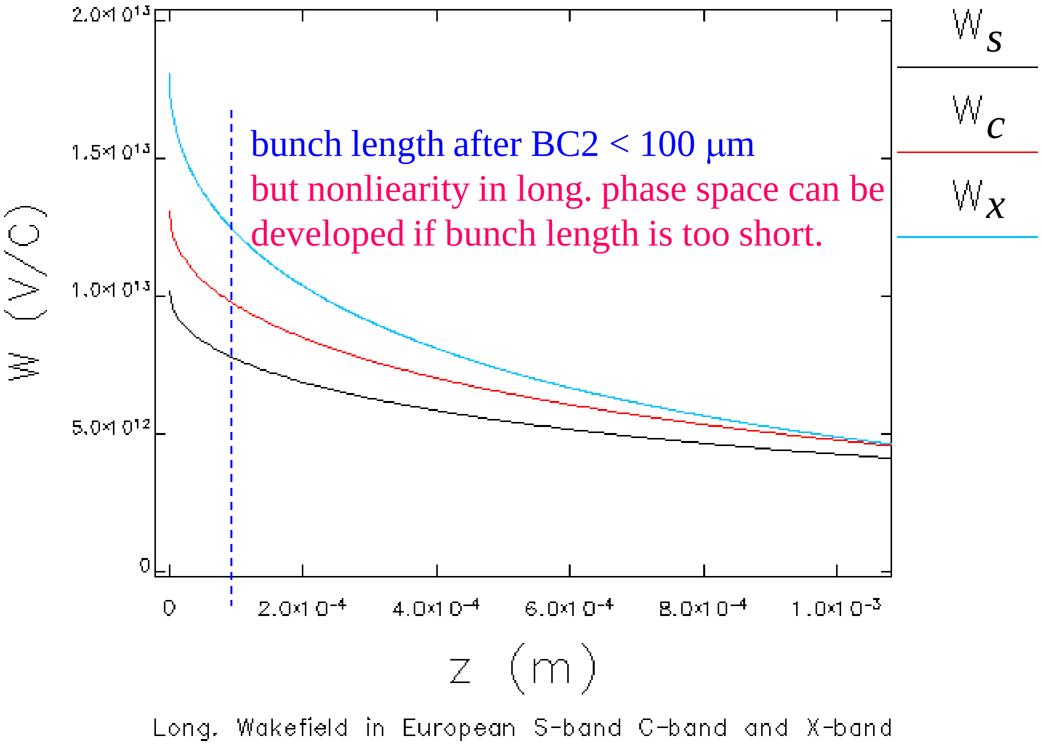
sensitivity of modulator error = high due to high SLED-II gain & smaller RF stations.

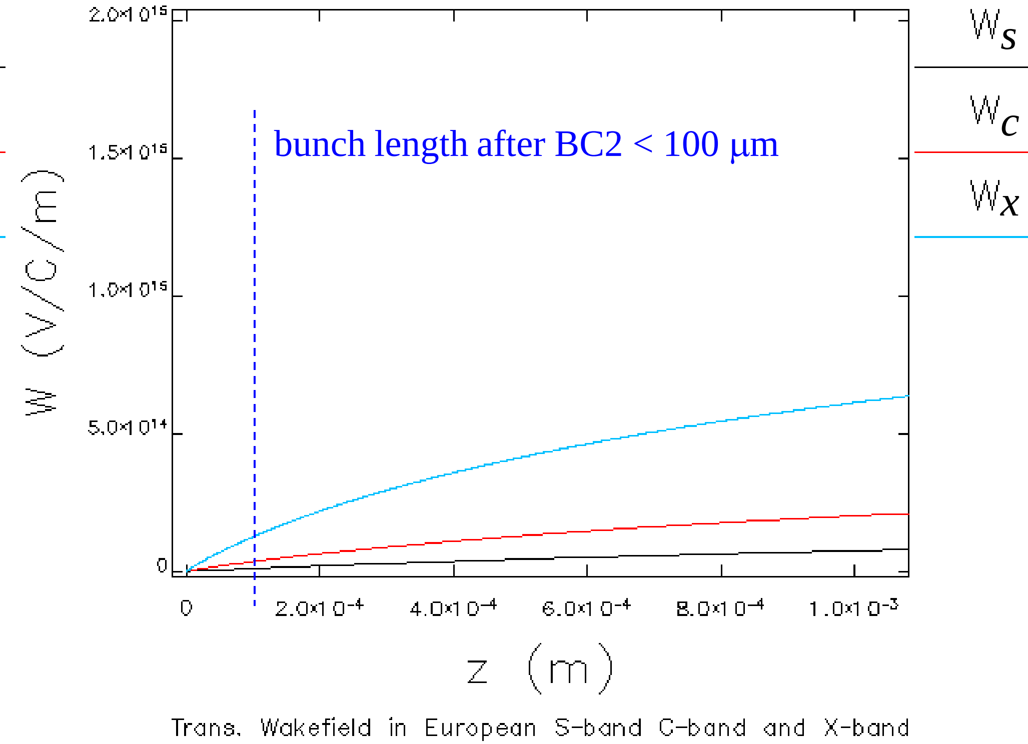
Note that one X-band klystron (SLED-II) is about 3 times (2 times) expensive than those of S- and C-bands.

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.

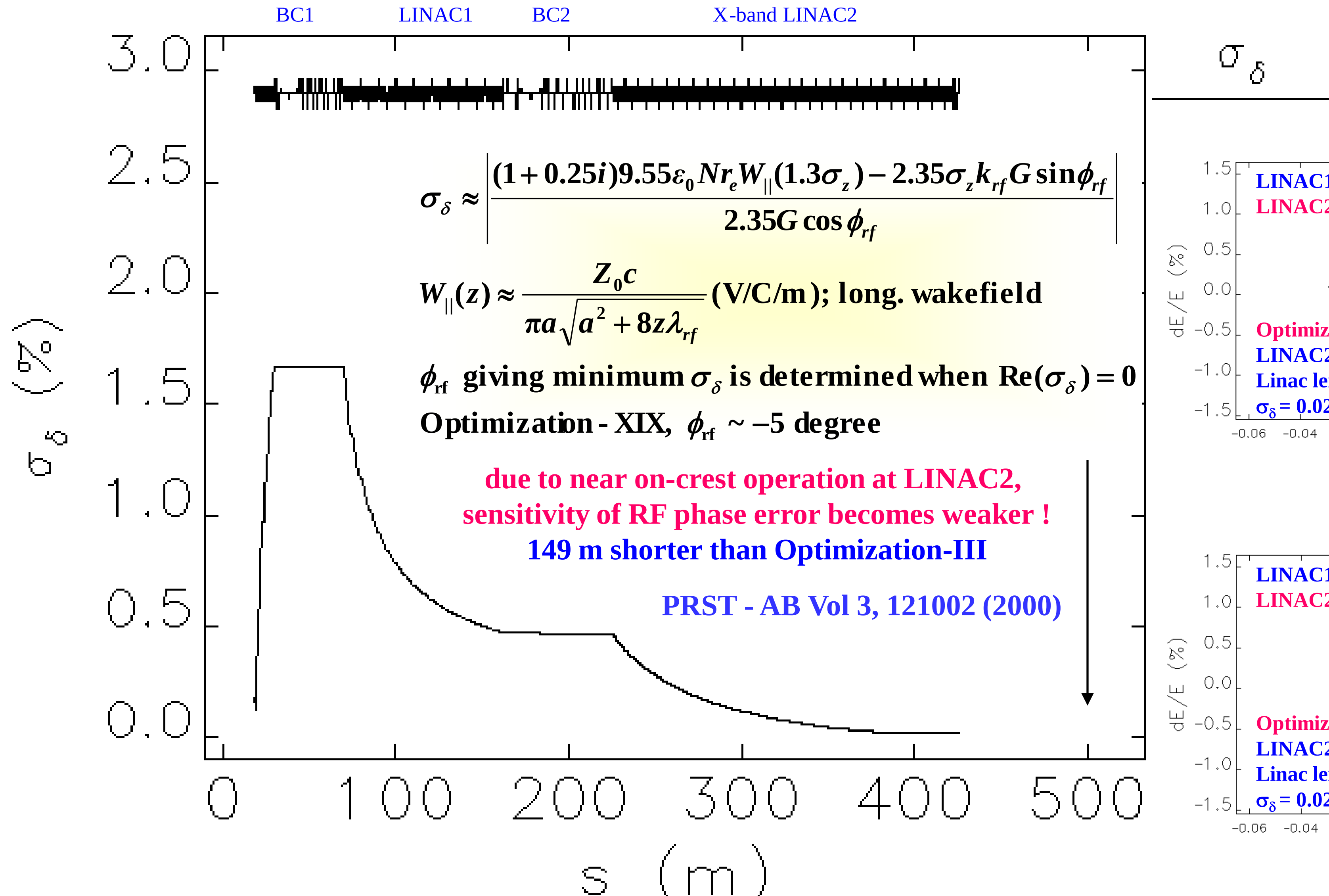
Transverse Short-range Wakefields: Strong if bunch length is longer (before BC1). Impact of the transverse short-range wakefields after BC2 is weak enough even though we use a high frequency RF linac after BC2.





Performance of X-band based LINAC2

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



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

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

ϕ_{rf} giving minimum σ_δ is determined when $\mathrm{Re}(\sigma_\delta) = 0$

Optimization-XIX, $\phi_{rf} \sim -5$ 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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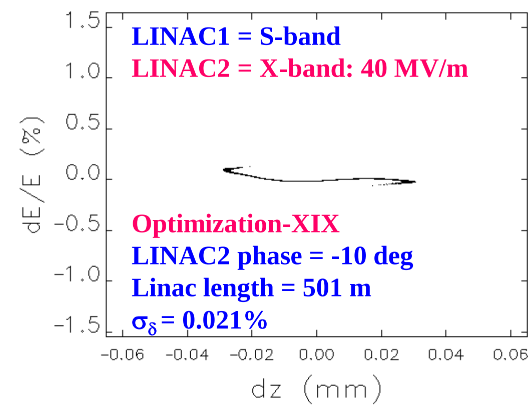
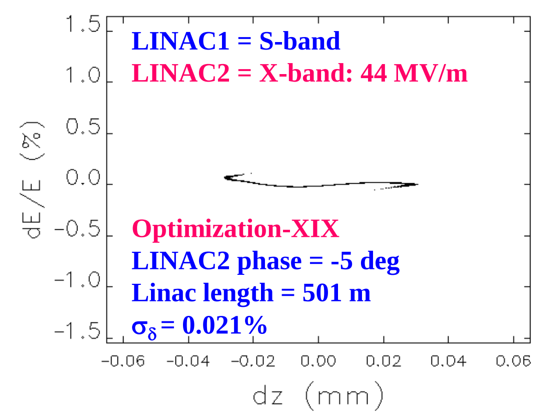
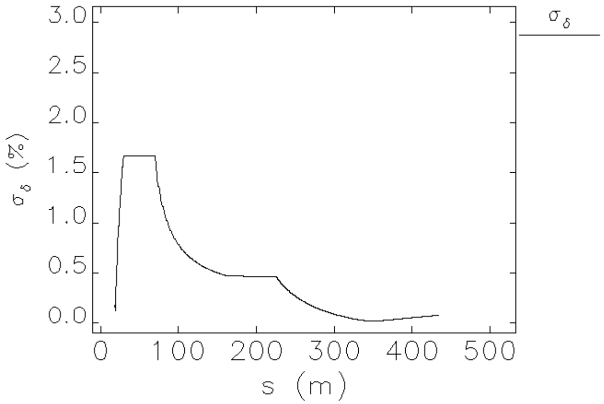


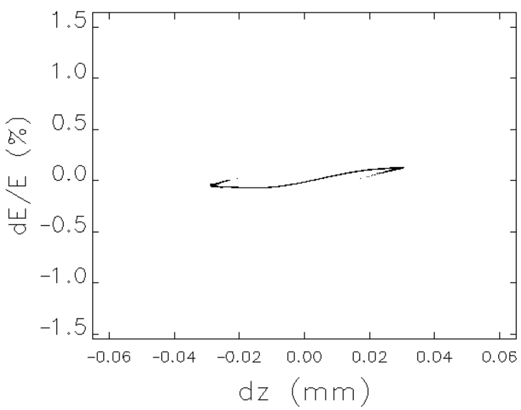


RF Amplitude & Phase for Chirping Control

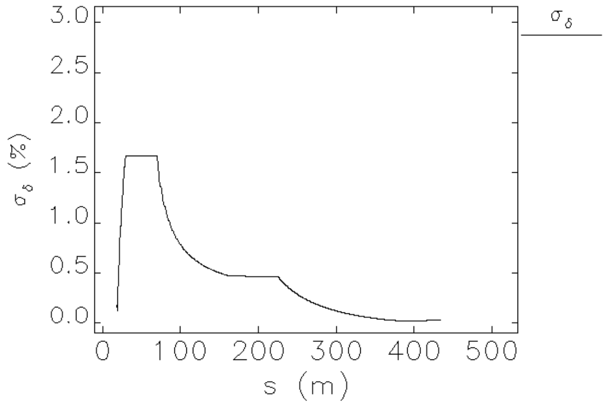
X-band based SwissFEL Optimization-XIX

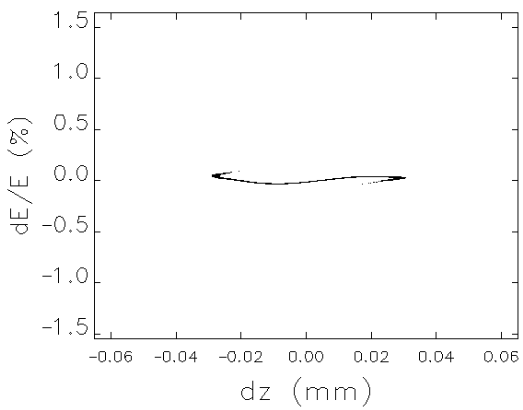
gradient : 40 MV/m
phase: +5 deg
σ_δ = 0.074%



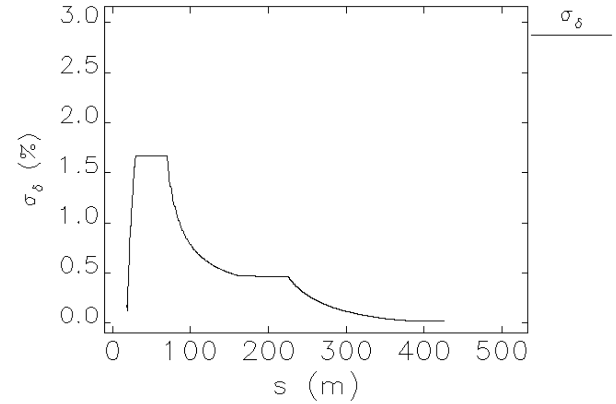


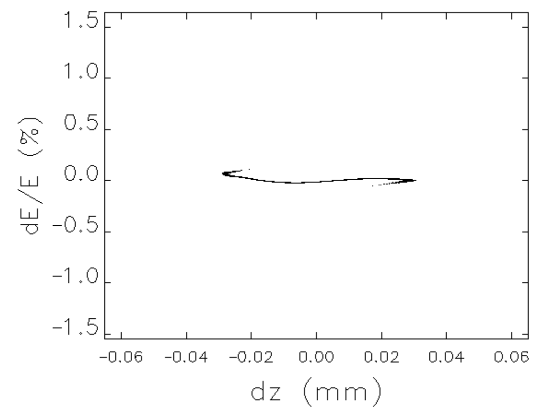
gradient : 40 MV/m
phase: -5 deg
σ_δ = 0.032%





gradient : 44 MV/m
phase: -5 deg
σ_δ = 0.024%

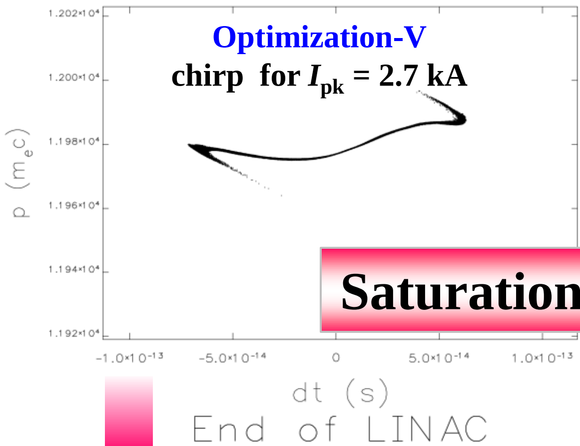


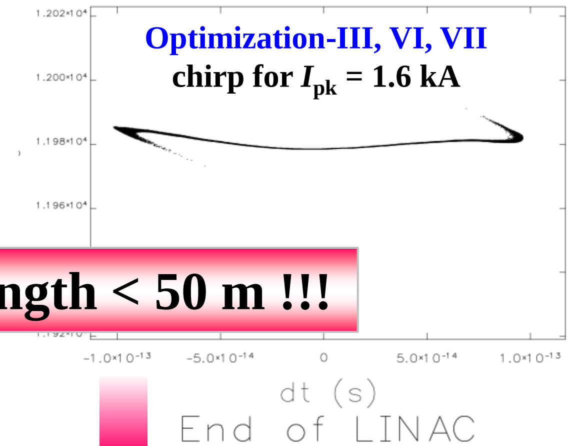


Impact of Energy Chirping on XFEL Photons

Idaho Accelerator Center

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.**

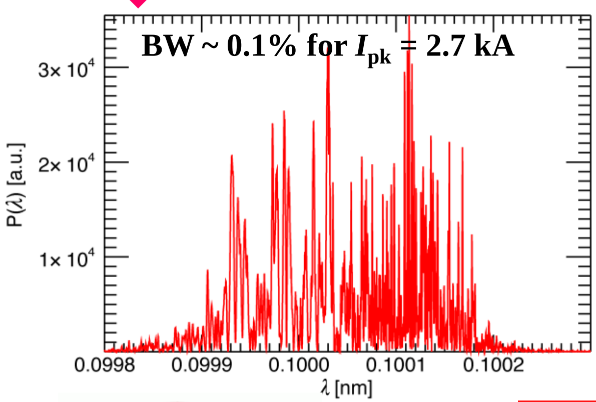


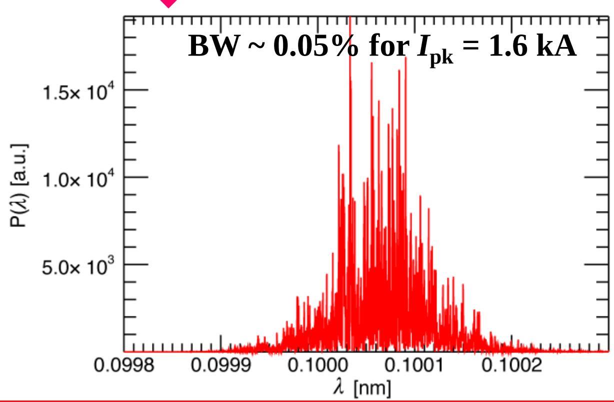


Saturation Length < 50 m !!!

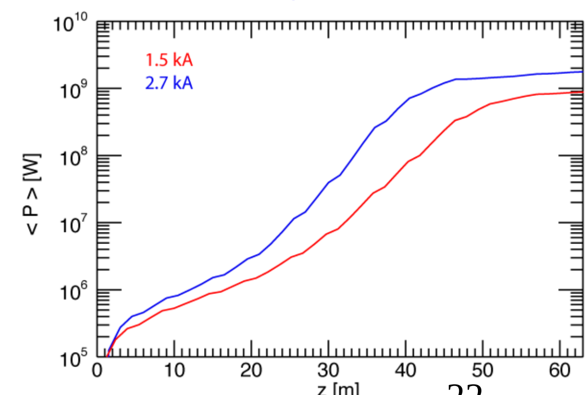
Optimization-III & V
S-band based Linacs
Linac Length = 650 m

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





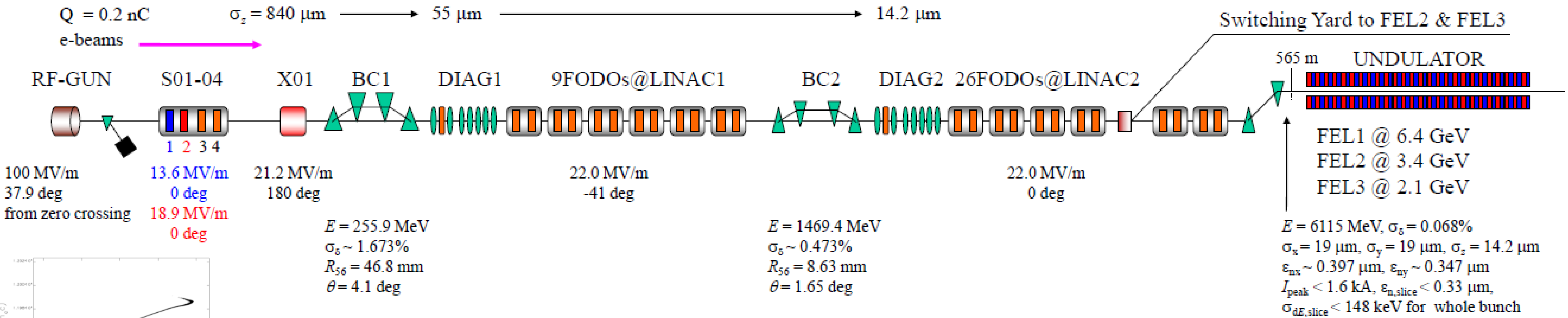
wavelength = 0.1 nm @ FEL1
no of photon per pulse ~ 1.0×10^{11}
saturation length ~ 40 m with 2.7 kA
saturation length ~ 48 m with 1.6 kA

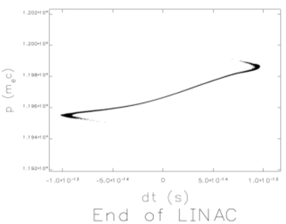


Energy Chirp Control with S-band Linac

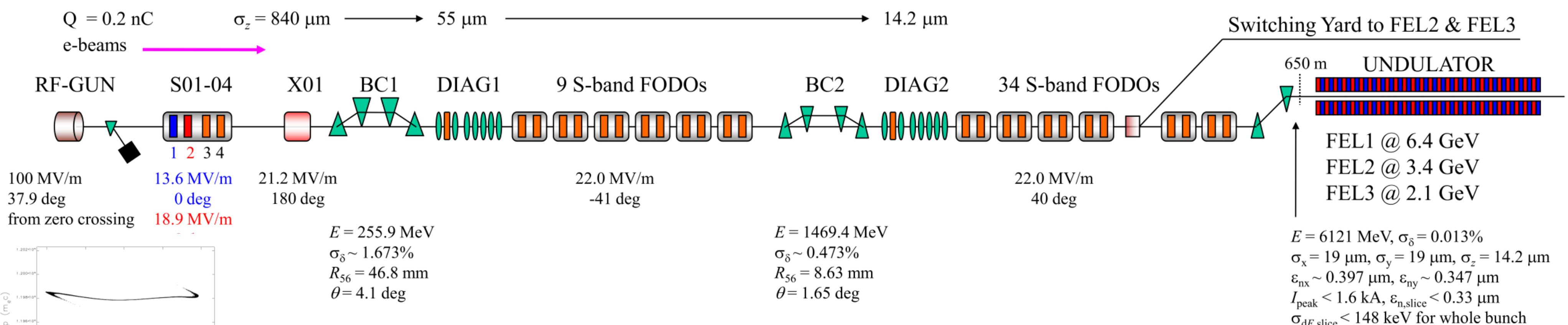
Idaho Accelerator Center

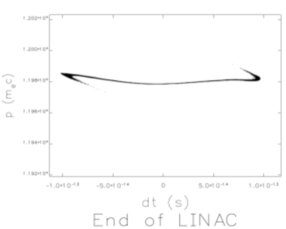
ASTRA up to exit of SB02 & ELEGANT from exit of SB02 to consider space chare, CSR, ISR, and wakefields !





SwissFEL Optimization-I with S-band RF Linacs

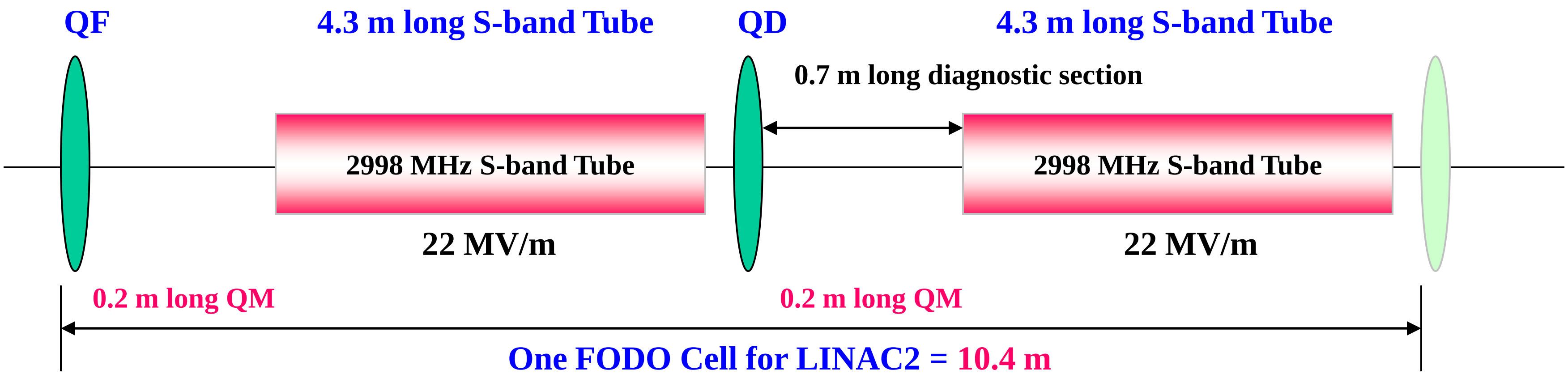




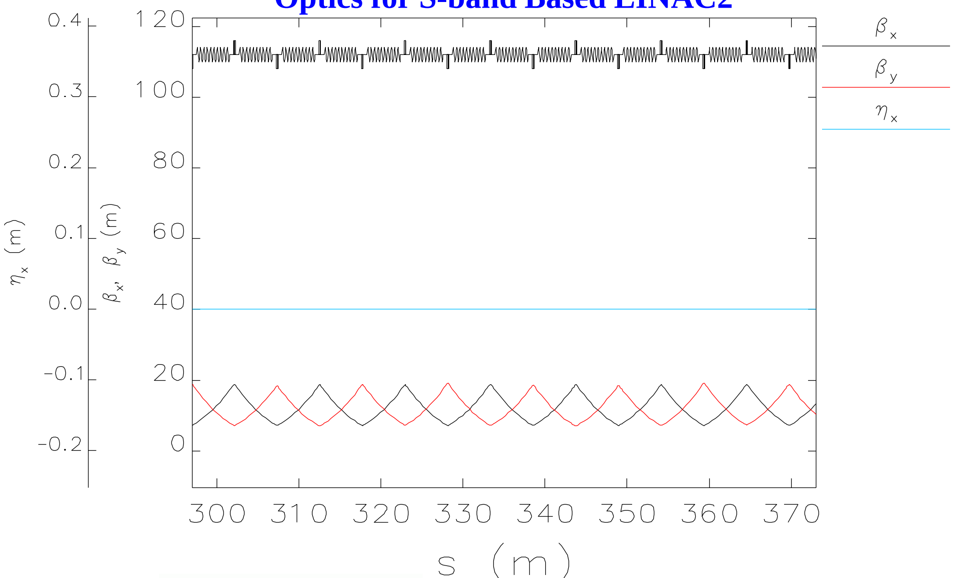
SwissFEL Optimization-III with a longer S-band RF Linacs for Chirp Compensation

SwissFEL - S-band based LINAC2 after BC2

LINAC2 for Optimization-III



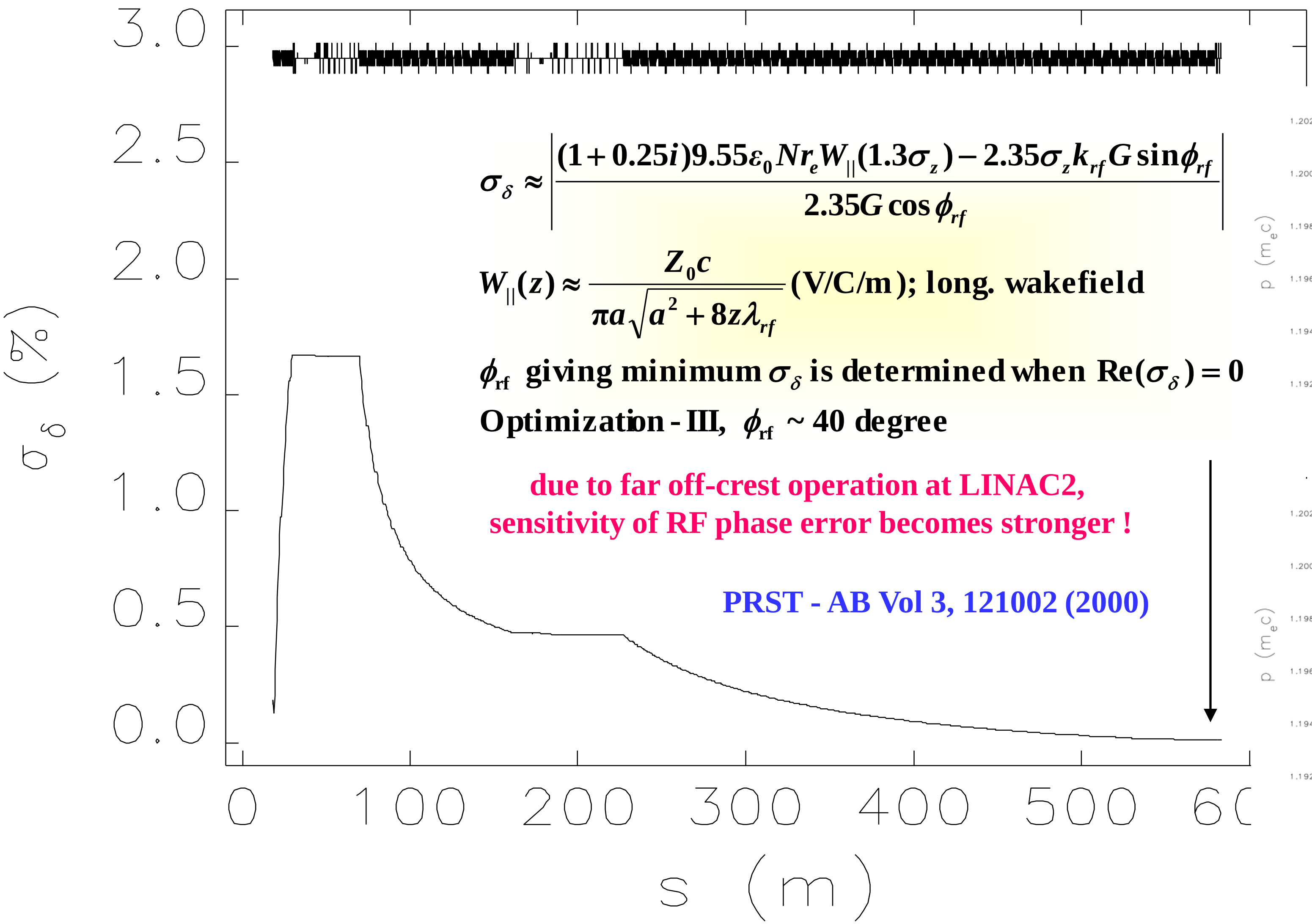
Optics for S-band Based LINAC2



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

SwissFEL - Performance of S-band LINAC2

LINAC2 for Optimization-III



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

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

ϕ_{rf} giving minimum σ_δ is determined when $\mathrm{Re}(\sigma_\delta) = 0$

Optimization-III, ϕ_{rf} ~ 40 degree

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

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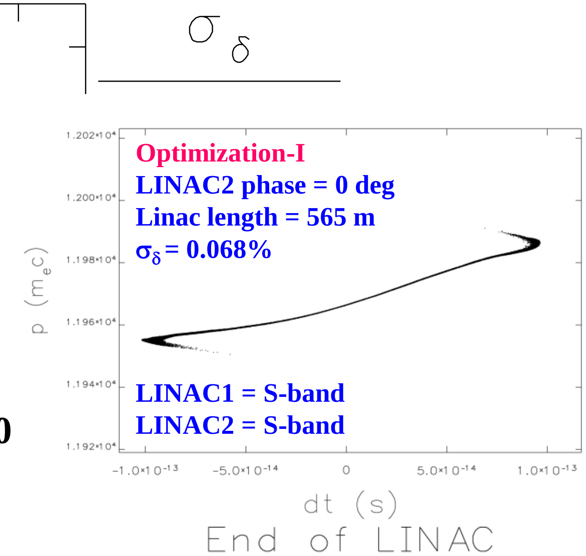
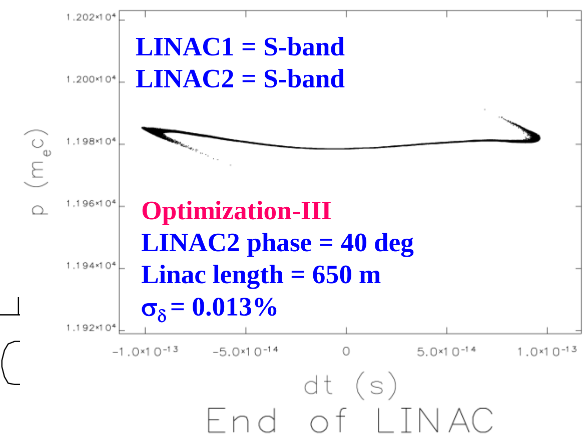
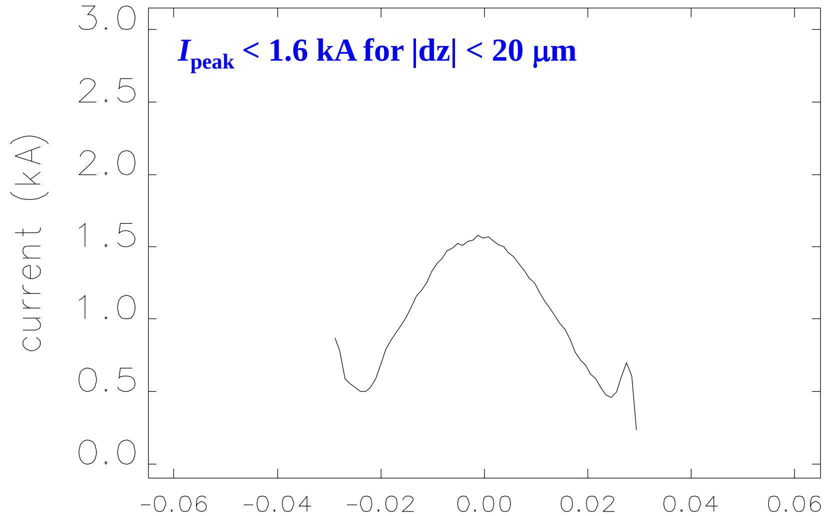
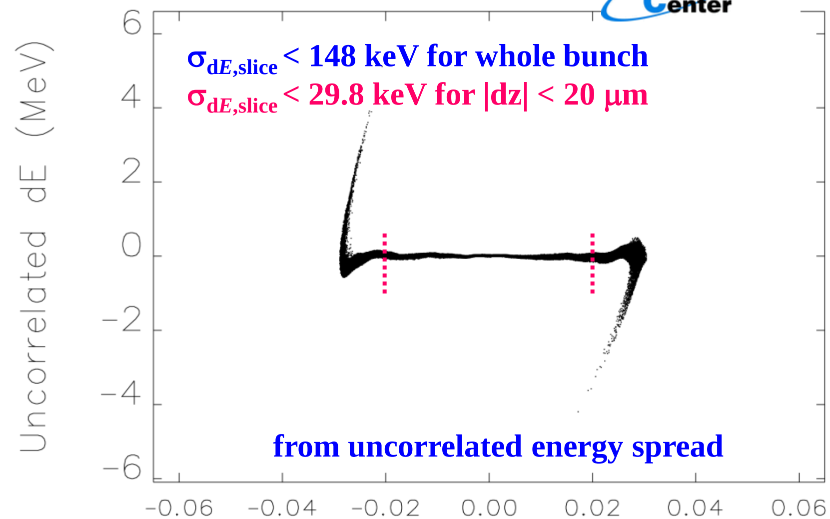


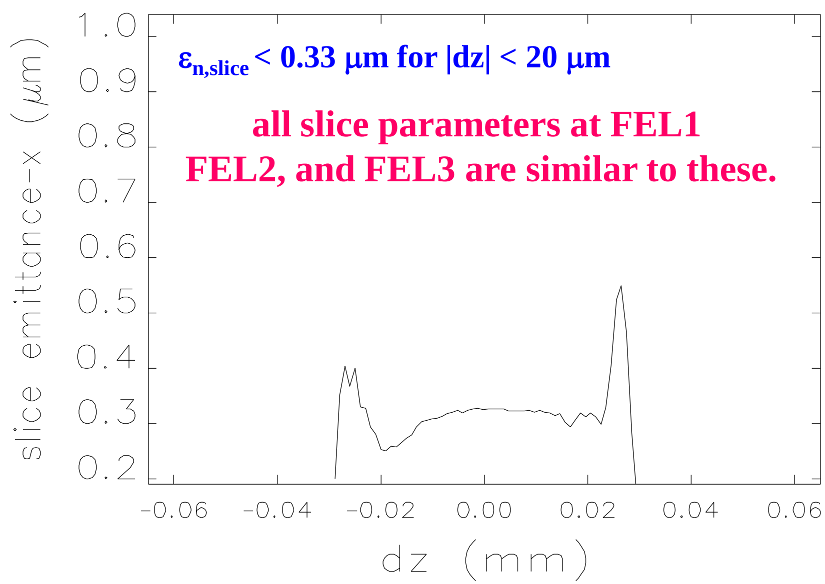


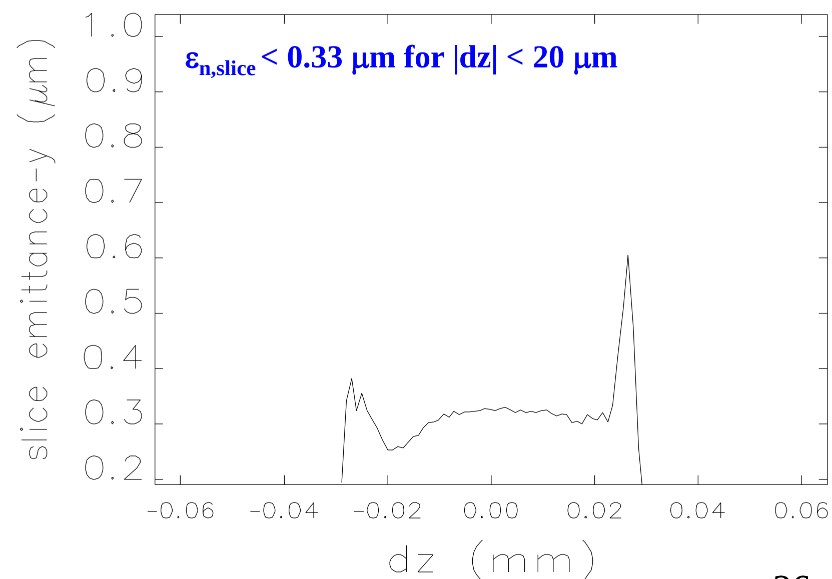
Performance of S-band based LINAC2



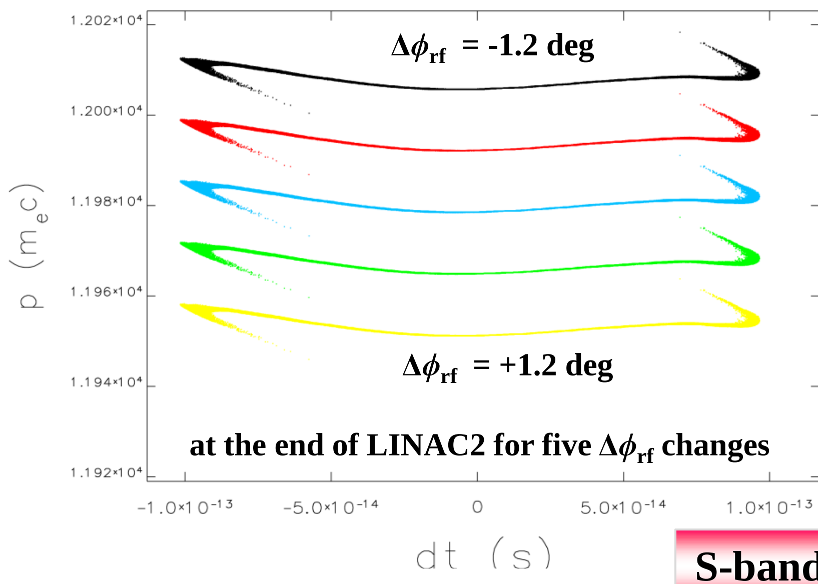


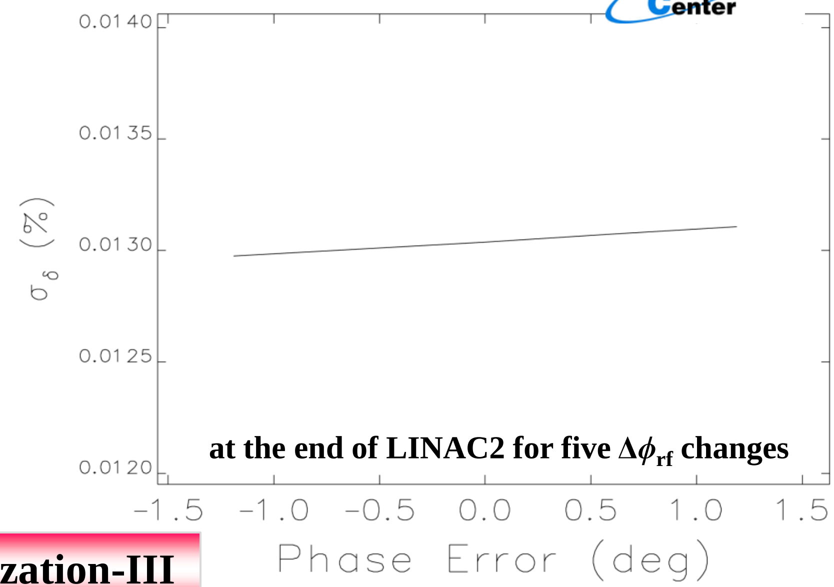
Slice Parameters at the end of LINAC2 (~ 6 GeV) of Optimization-III



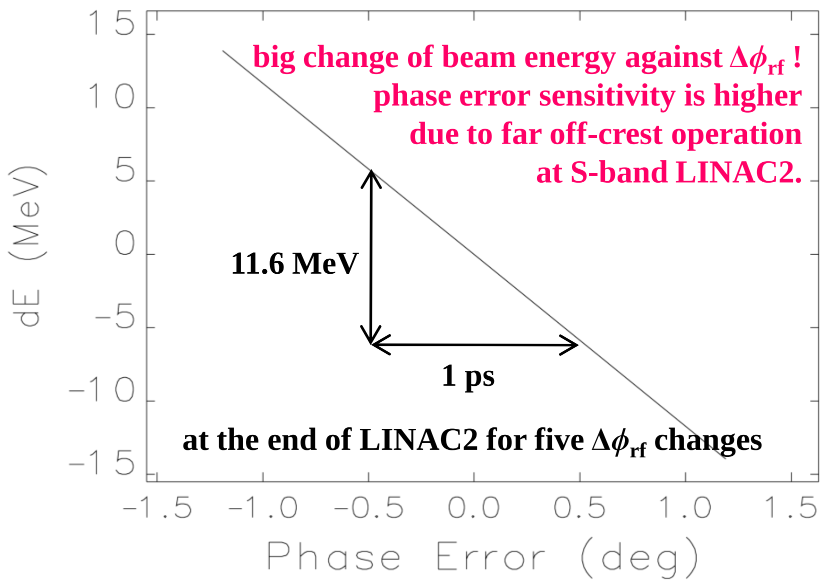


S-band LINAC2 - $\Delta\phi_{rf}$ Sensitivity





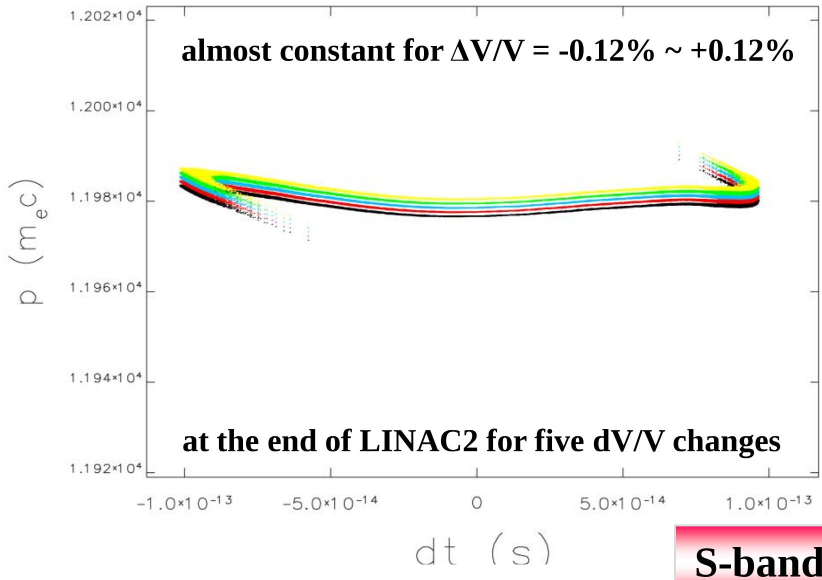
S-band Optimization-III

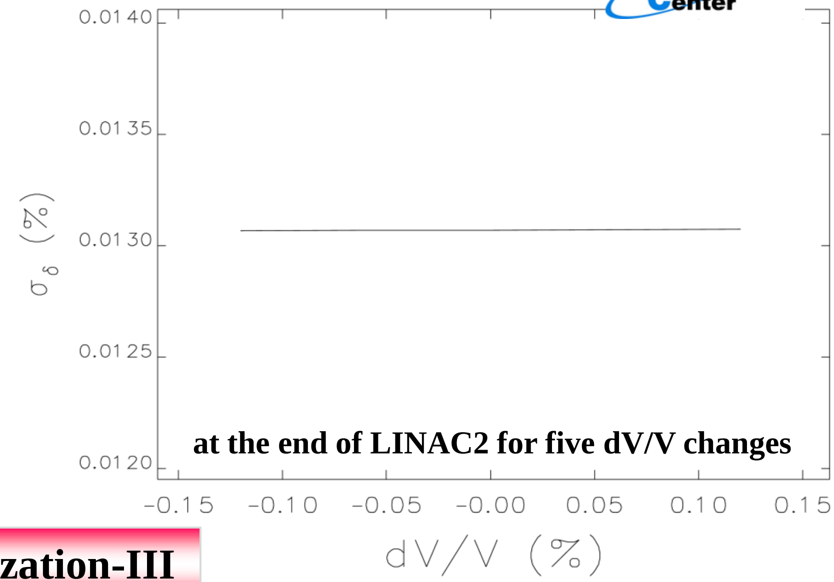


(top left) change of longitudinal phase space, (top right), change of projected relative energy spread, (bottom left) change of beam energy when RF phase of an RF station in S-band LINAC2 is changed by ±1.2 deg (= 0.4 deg in rms) with five steps (step size = 0.6 deg). please note that ±1.2 deg in S-band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

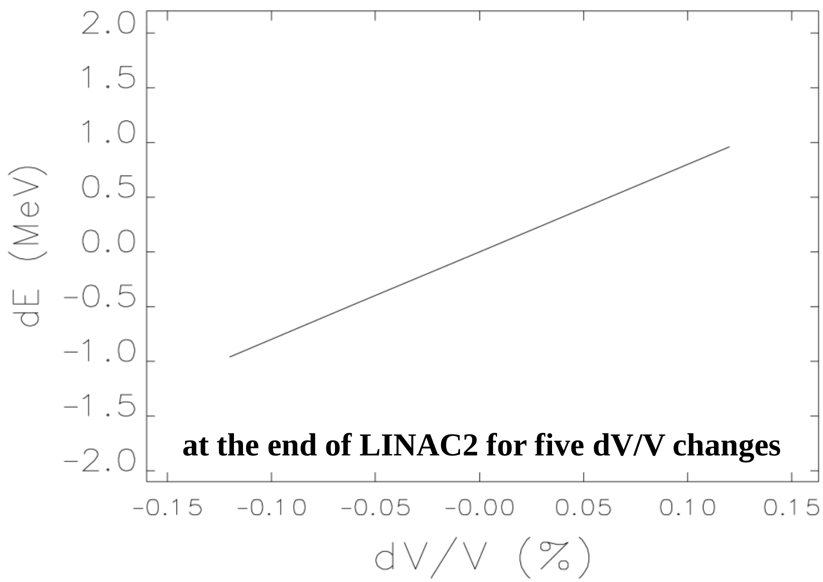
dE ~ 27.9 MeV for 2.4 ps, dE ~ 11.6 MeV for 1.0 ps
dE/E ~ 0.19% for $\Delta\phi_{rf}$ = 1.0 deg (= 1 ps)
energy spread change ~ 0.5% for $\Delta\phi_{rf}$ = 1.0 deg
In this case, XFEL wavelength change ~ 0.38%

S-band LINAC2 - dV/V Sensitivity





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 ±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 ~ 1.92 MeV for dV/V = ±0.12%
dE/E ~ 0.03% for dV/V = ±0.12%
energy spread change ~ 0.045% for dV/V = ±0.12%
In this case, XFEL wavelength change ~ 0.06%

S-band LINAC2 - Alignment Issues

Idaho Accelerator Center

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.

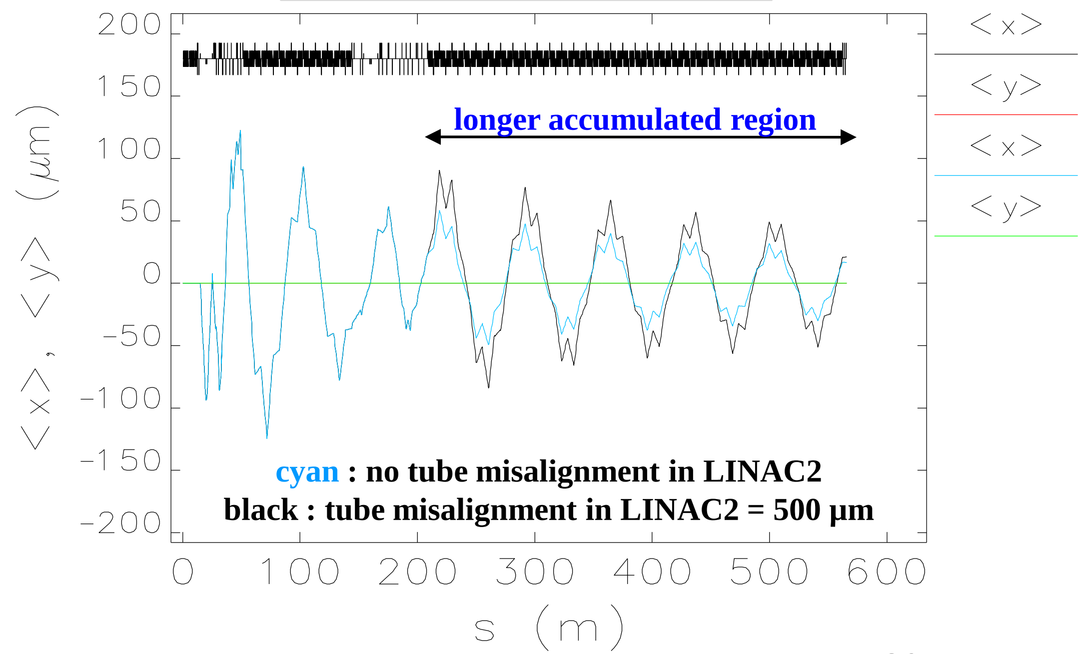
PRST - AB Vol 3, 121002 (2000) & LCLS-TN-01-1

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

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

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.

S-band Optimization-III



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.

PRST - AB Vol 3, 121002 (2000) & LCLS-TN-01-1

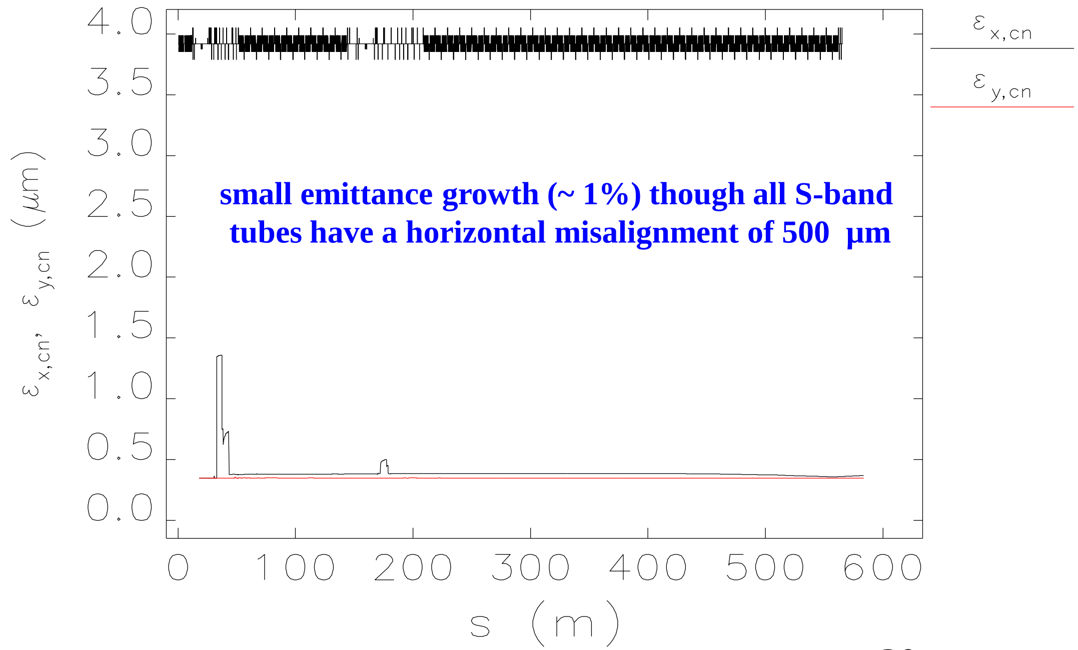
$$W_\perp(z) \approx \frac{2Z_0 cz}{\pi a^3 \sqrt{a^2 + 5z\lambda_{rf}}} \text{(V/C/m}^2\text{)}; \quad \text{transverse wakefield, } Z_0 \approx 377\,\Omega$$

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

Even though all 68 S-band tubes in LINAC2 have a horizontal misalignment of 500 μm, emittance growths due to the transverse short-range wakefield at the end of linac are small enough:
$\Delta\varepsilon_{nx} \sim 0.004$ μm, $\Delta\varepsilon_{ny} \sim 0.001$ μm

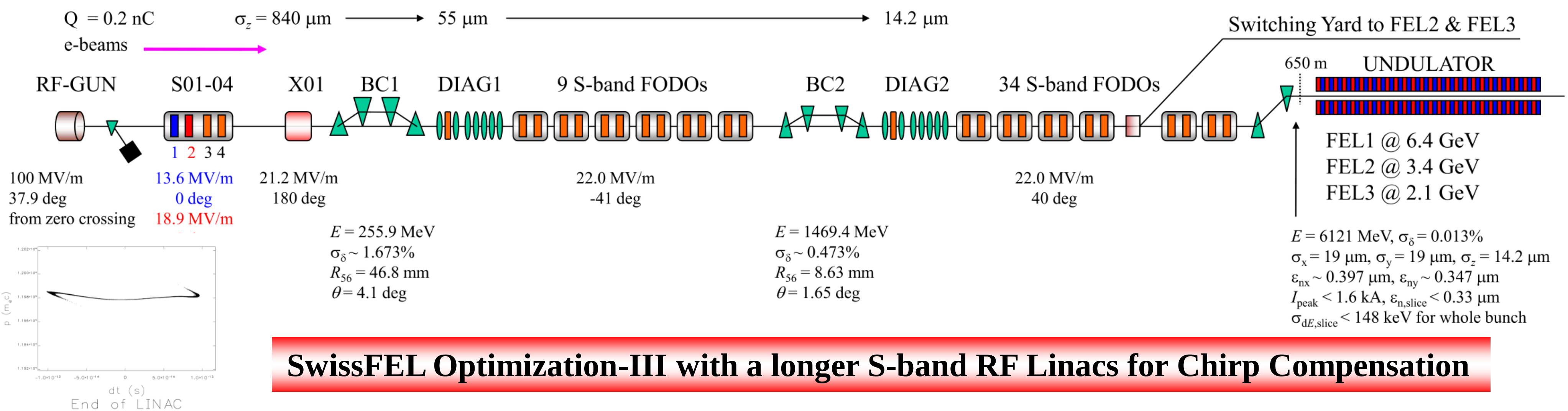
Therefore, S-band tubes can be aligned with the normal alignment technology.

S-band Optimization-III

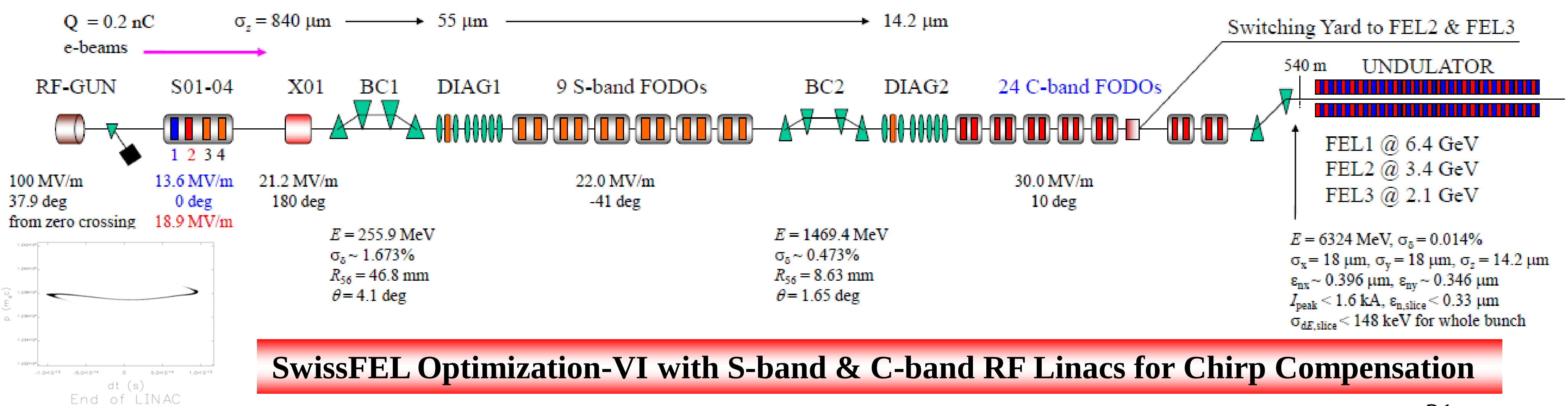


Energy Chirp Control with C-band Linac

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



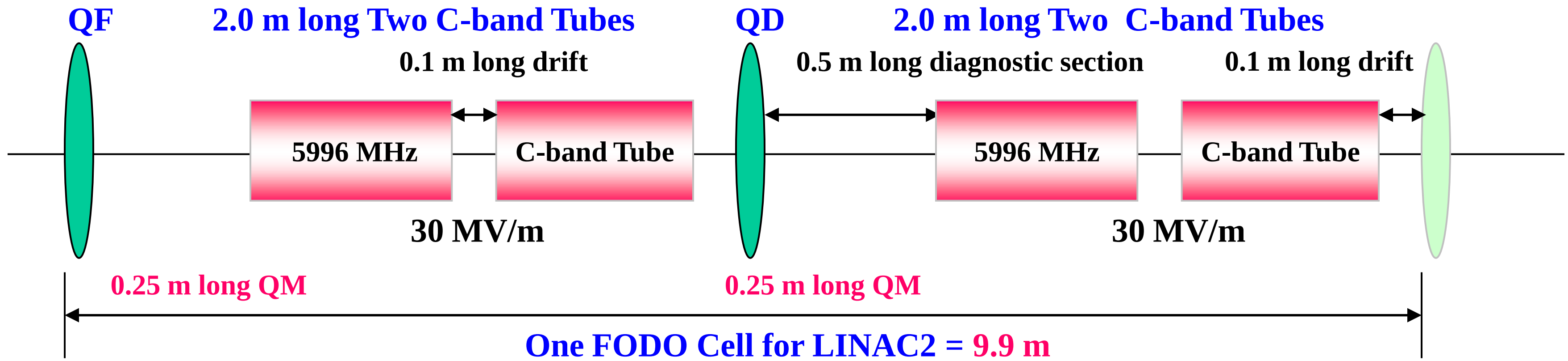
SwissFEL Optimization-III with a longer S-band RF Linacs for Chirp Compensation

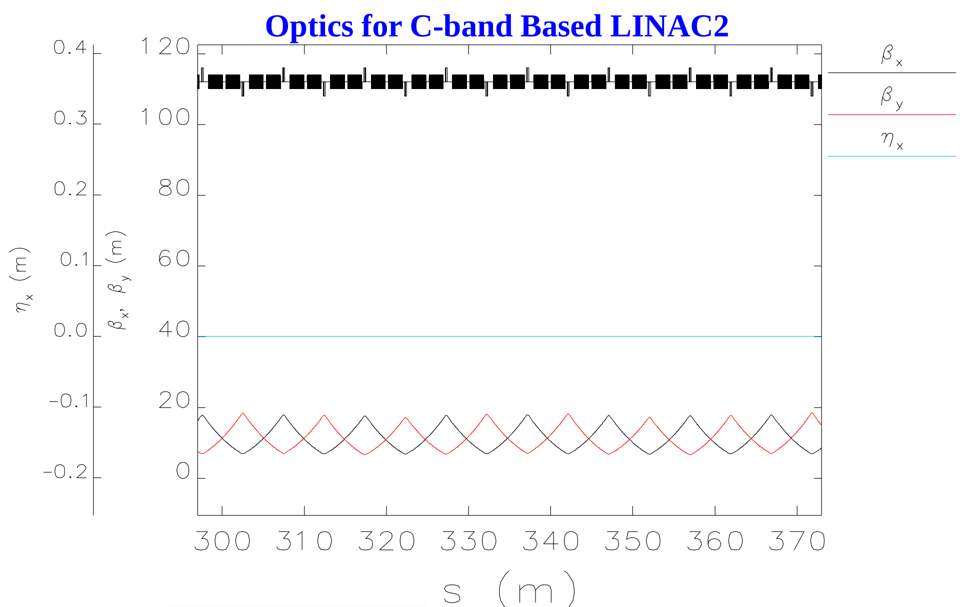


SwissFEL Optimization-VI with S-band & C-band RF Linacs for Chirp Compensation

C-band based LINAC2 after BC2

LINAC2 for Optimization-VI



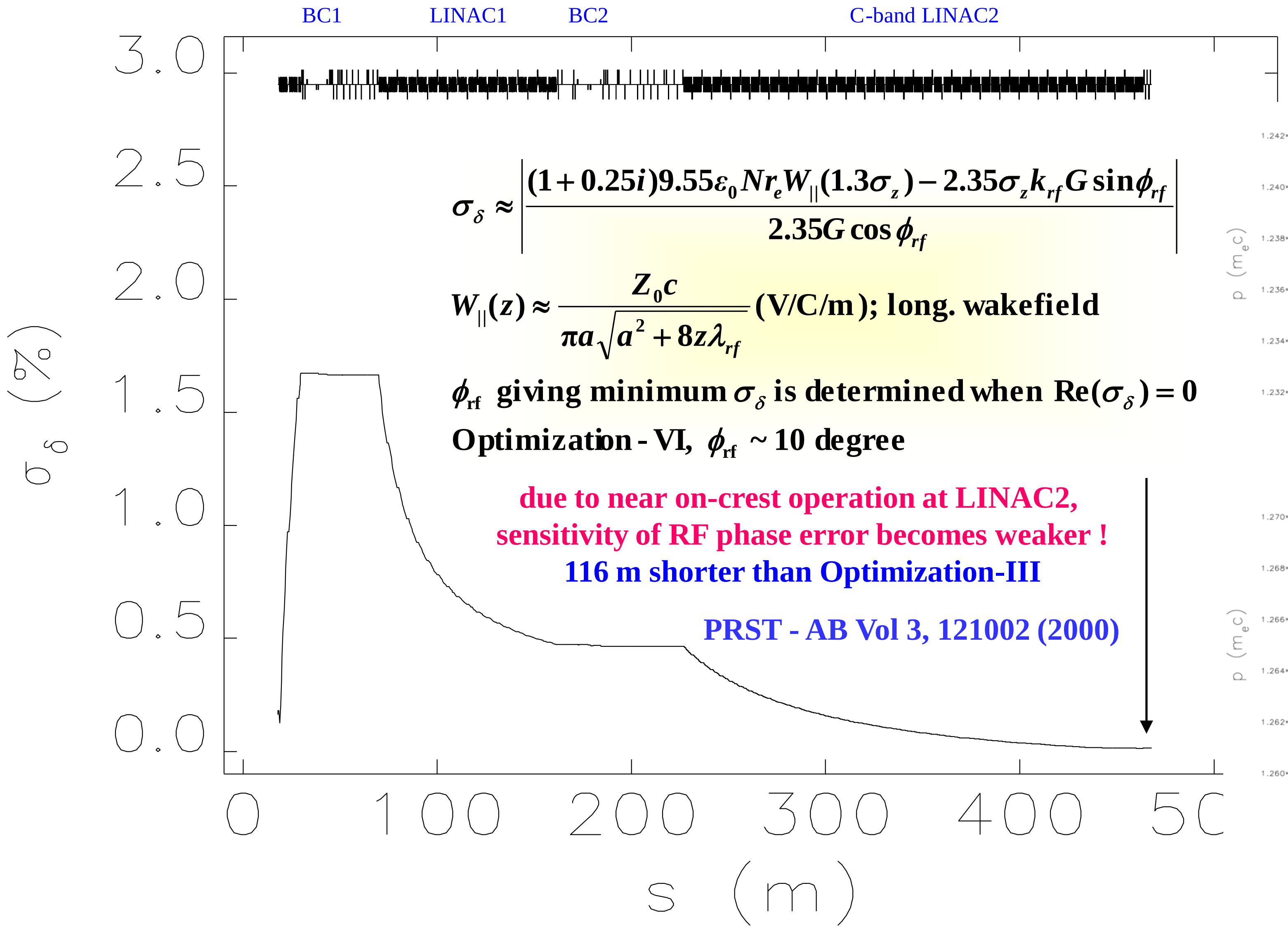


length of one FODO cell in LINAC2
= four 2.0 m long PSI standard C-band tubes
+ two 0.5 m long PSI standard diagnostic sections
+ four 0.1 m long drifts for component assembly
+ two 0.25 m long QMs = 9.9 m

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 !



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

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

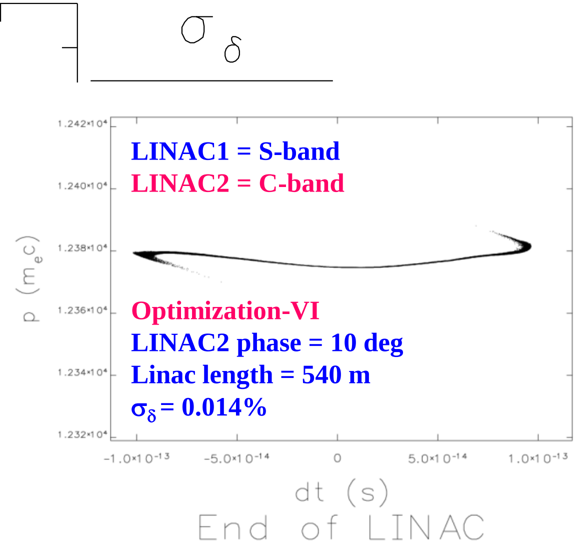
ϕ_{rf} giving minimum σ_δ is determined when $\mathrm{Re}(\sigma_\delta) = 0$

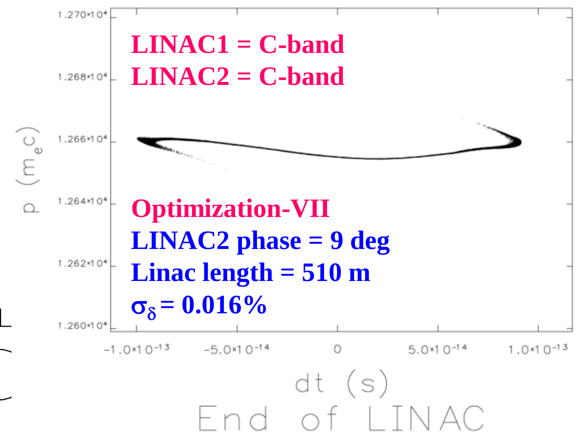
Optimization-VI, $\phi_{rf} \sim 10$ degree

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

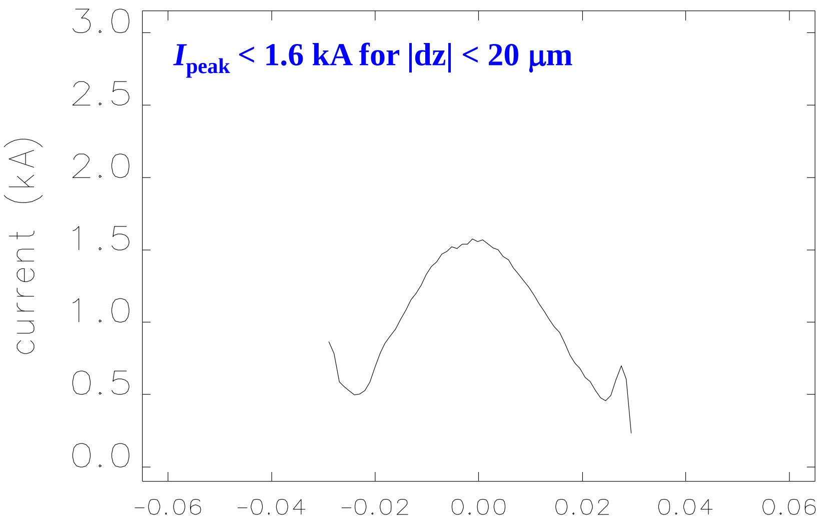
116 m shorter than Optimization-III

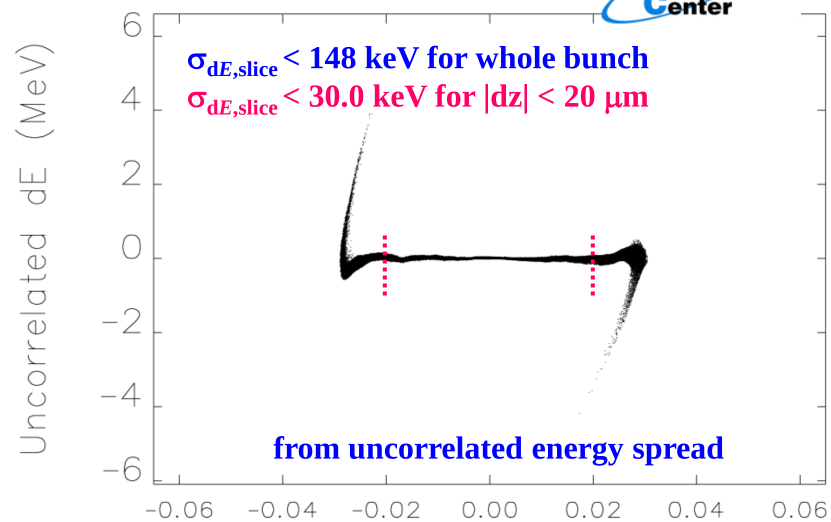
PRST - AB Vol 3, 121002 (2000)



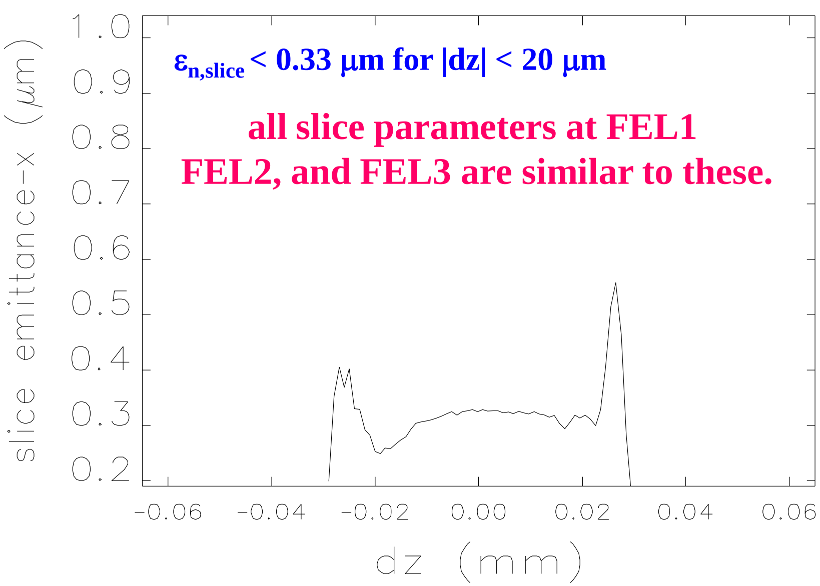


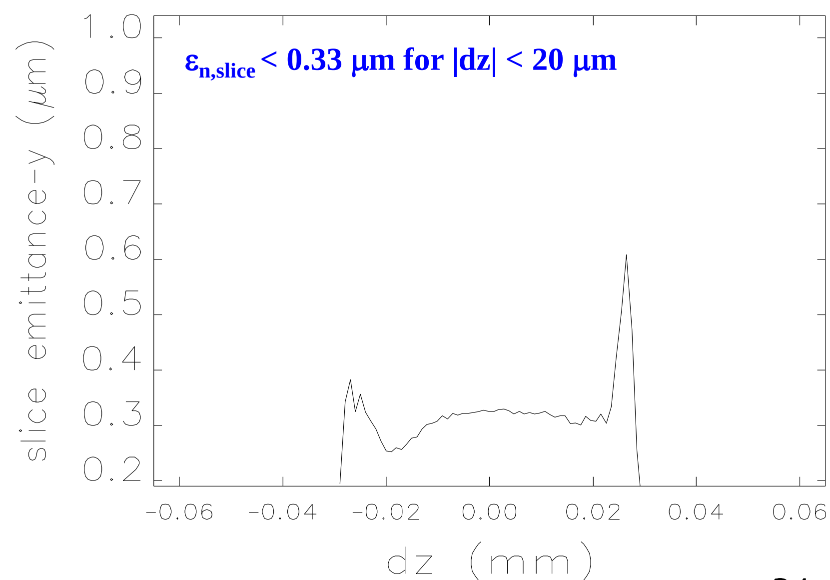
Performance of C-band based LINAC2



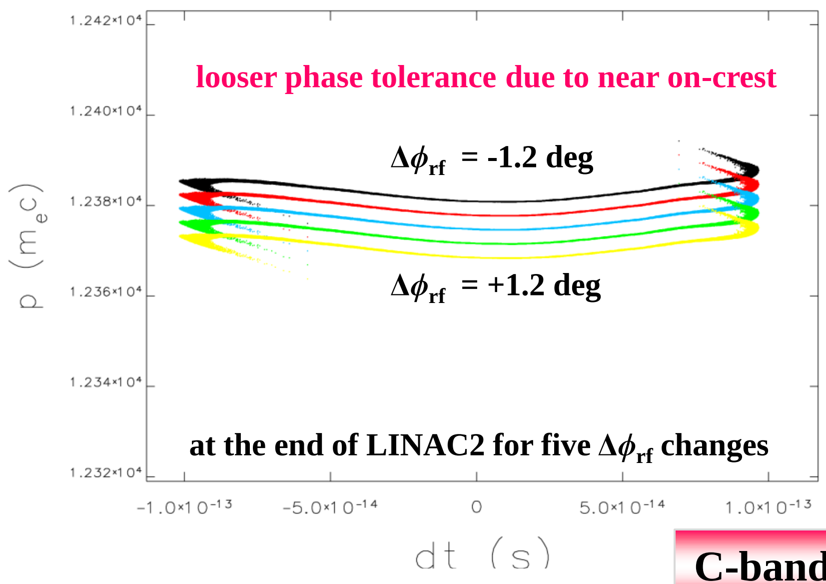


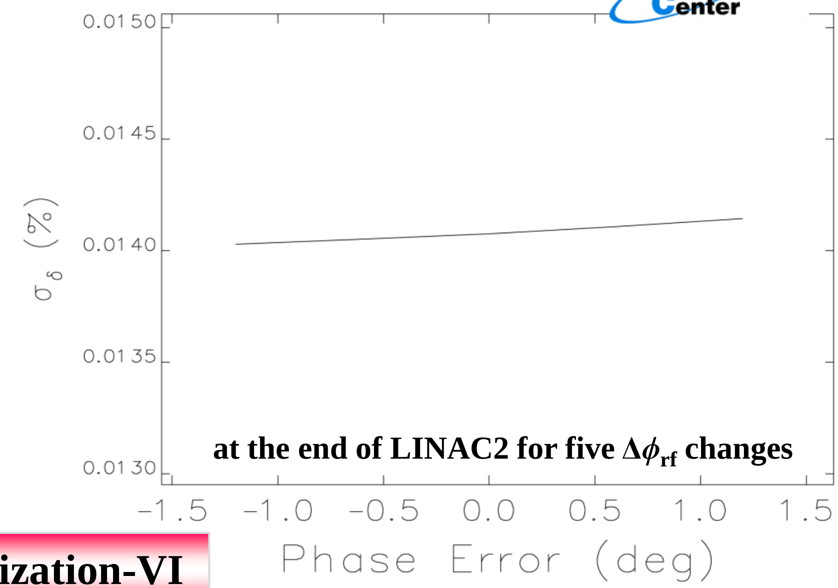
Slice Beam Parameters of Optimization-VI is exactly same as those of Optimization-III !



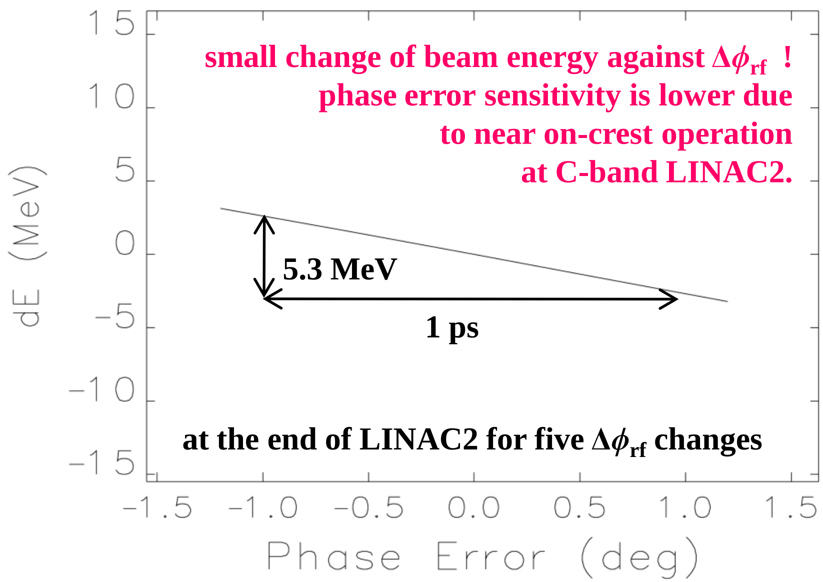


C-band LINAC2 - $\Delta\phi_{rf}$ Sensitivity





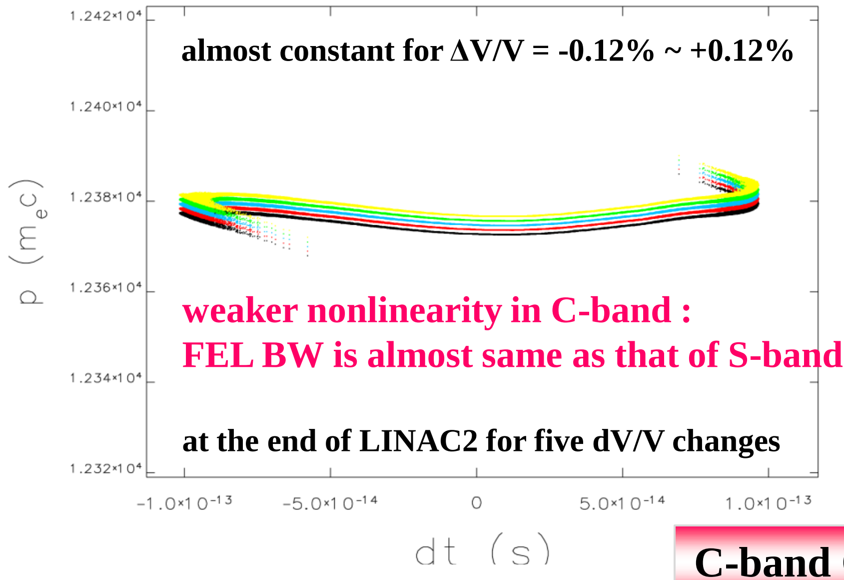
C-band Optimization-VI

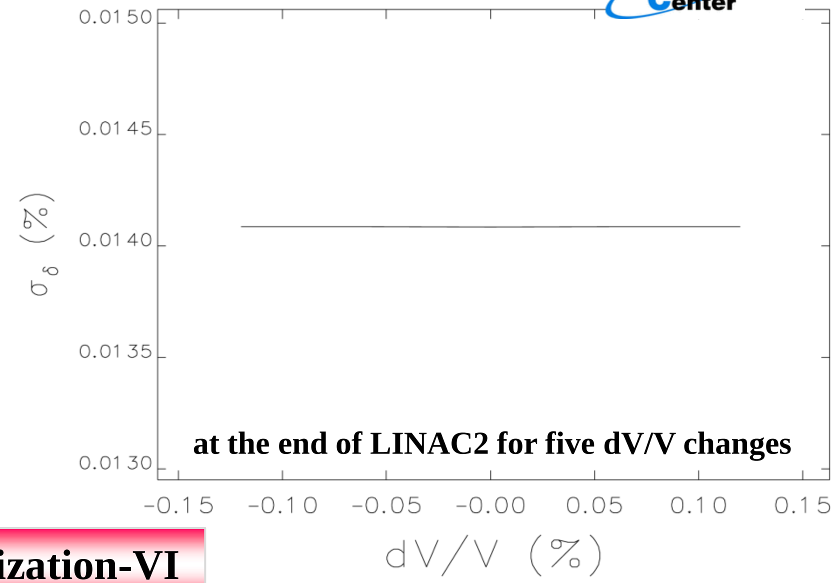


(top left) change of longitudinal phase space, (top right), change of projected relative energy spread, (bottom left) change of beam energy when RF phase of an RF station in C-band LINAC2 is changed by ±1.2 deg (= 0.4 deg in rms) with five steps (step size = 0.6 deg). please note that ±1.2 deg in C-band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

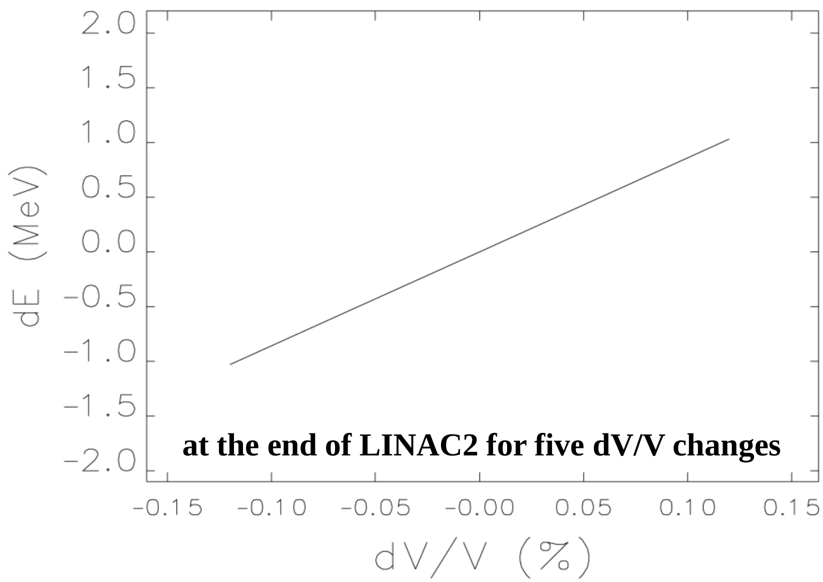
dE ~ 6.35 MeV for 1.2 ps, dE ~ 5.3 MeV for 1.0 ps
dE/E ~ 0.084% for $\Delta\phi_{rf}$ = 2.0 deg (= 1 ps)
energy spread change ~ 0.67% for $\Delta\phi_{rf}$ = 2.0 deg
In this case, XFEL wavelength change ~ 0.17%

C-band LINAC2 - dV/V Sensitivity





C-band Optimization-VI



(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

Idaho Accelerator Center

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.

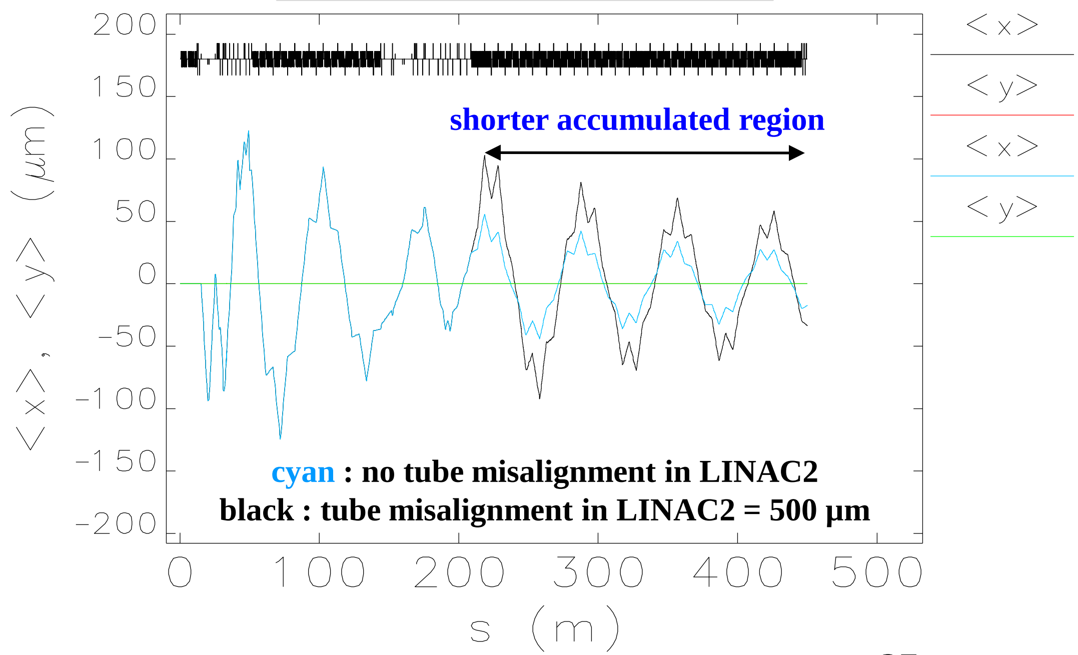
PRST - AB Vol 3, 121002 (2000) & LCLS-TN-01-1

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

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

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.

C-band Optimization-VI



C-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.

PRST - AB Vol 3, 121002 (2000) & LCLS-TN-01-1

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

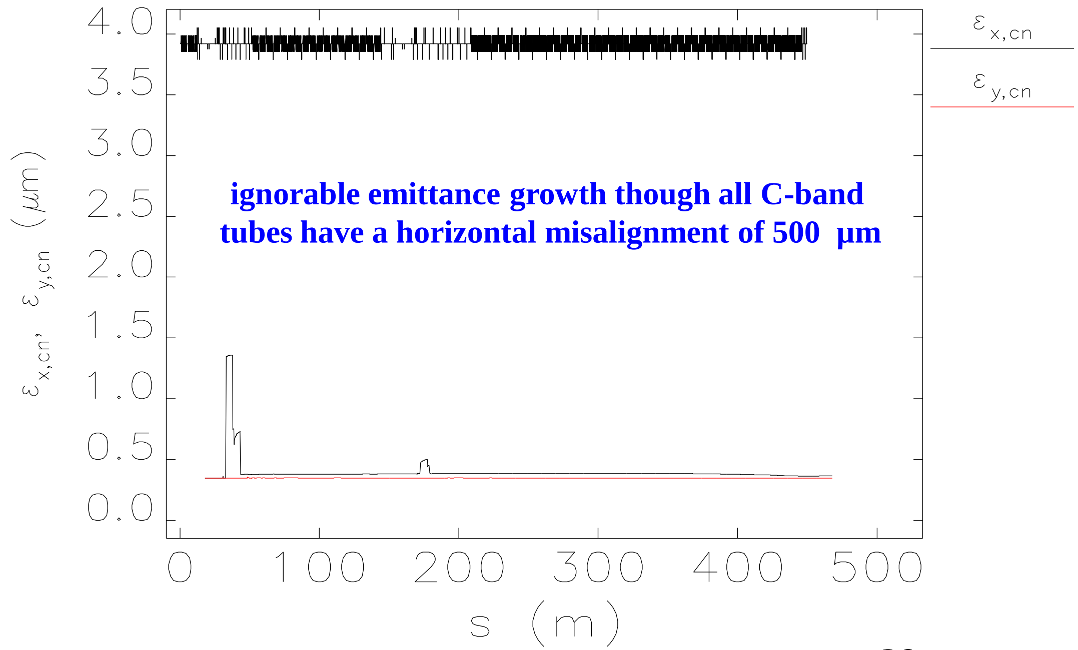
$$\frac{\varepsilon_0 + \Delta\varepsilon}{\varepsilon_0} \approx \sqrt{1 + \left(\frac{\pi r_e}{Z_0 c}\right)^2 \frac{N^2 \langle W_\perp \rangle^2 L^2 \beta}{\varepsilon_n \gamma} \Delta x^2}$$

Even though all 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:

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

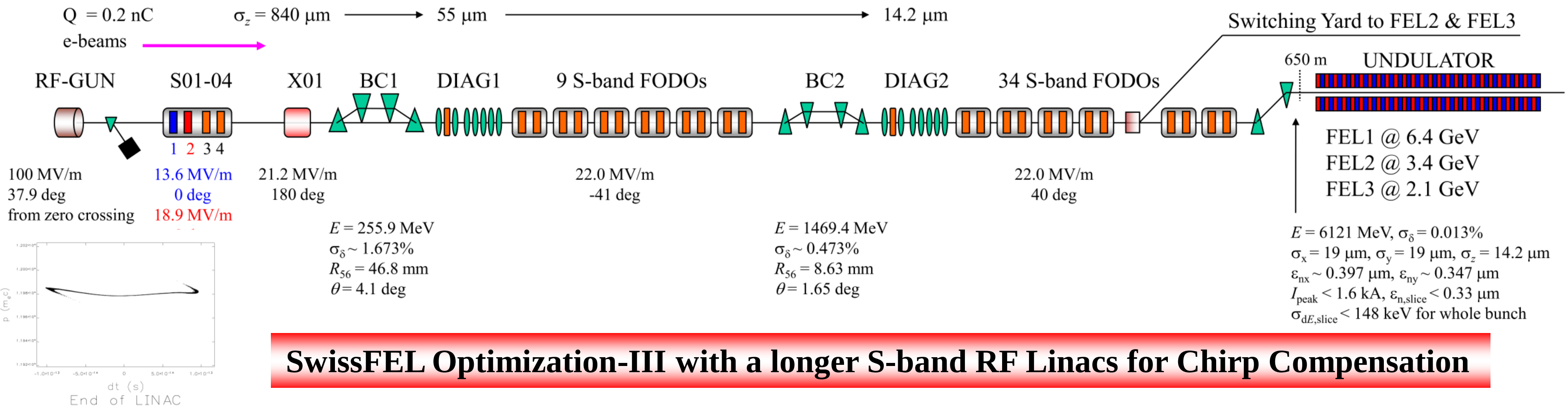
Therefore, C-band tubes can be aligned with the normal alignment technology.

C-band Optimization-VI

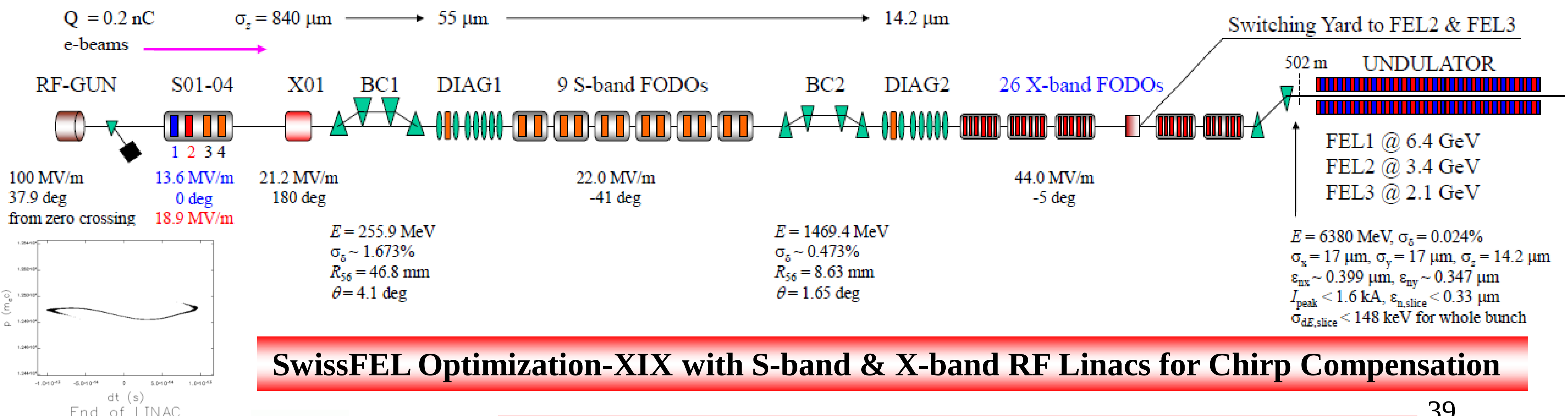


Energy Chirp Control with X-band Linac

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



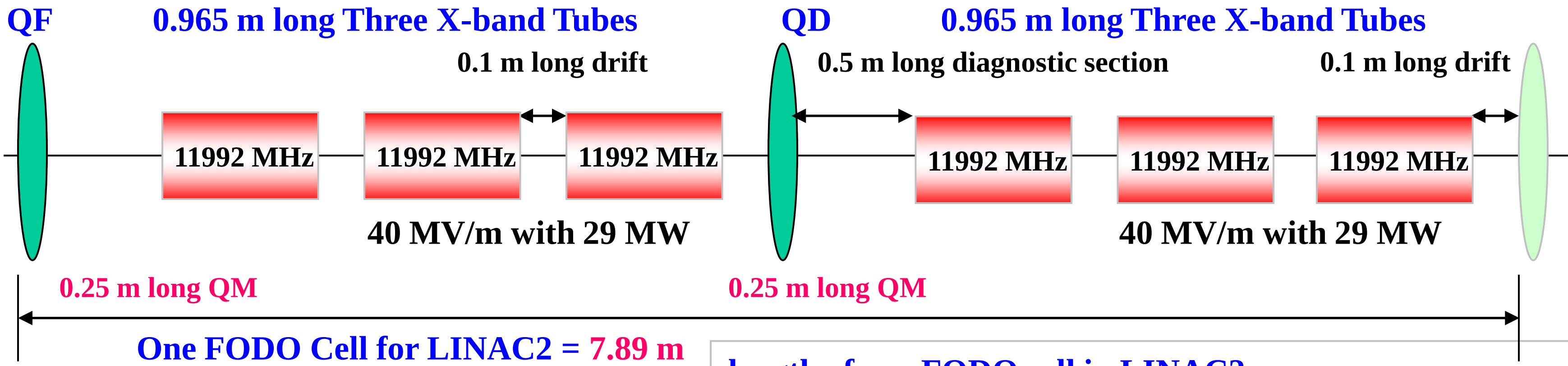
SwissFEL Optimization-III with a longer S-band RF Linacs for Chirp Compensation



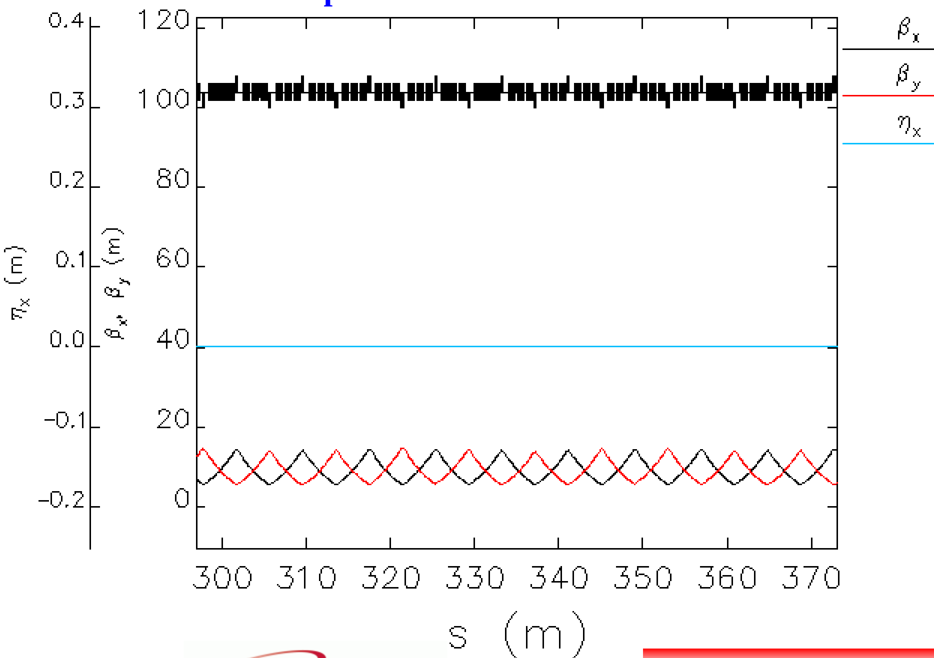
SwissFEL Optimization-XIX with S-band & X-band RF Linacs for Chirp Compensation

X-band based LINAC2 after BC2

LINAC2 for Optimization-XIX



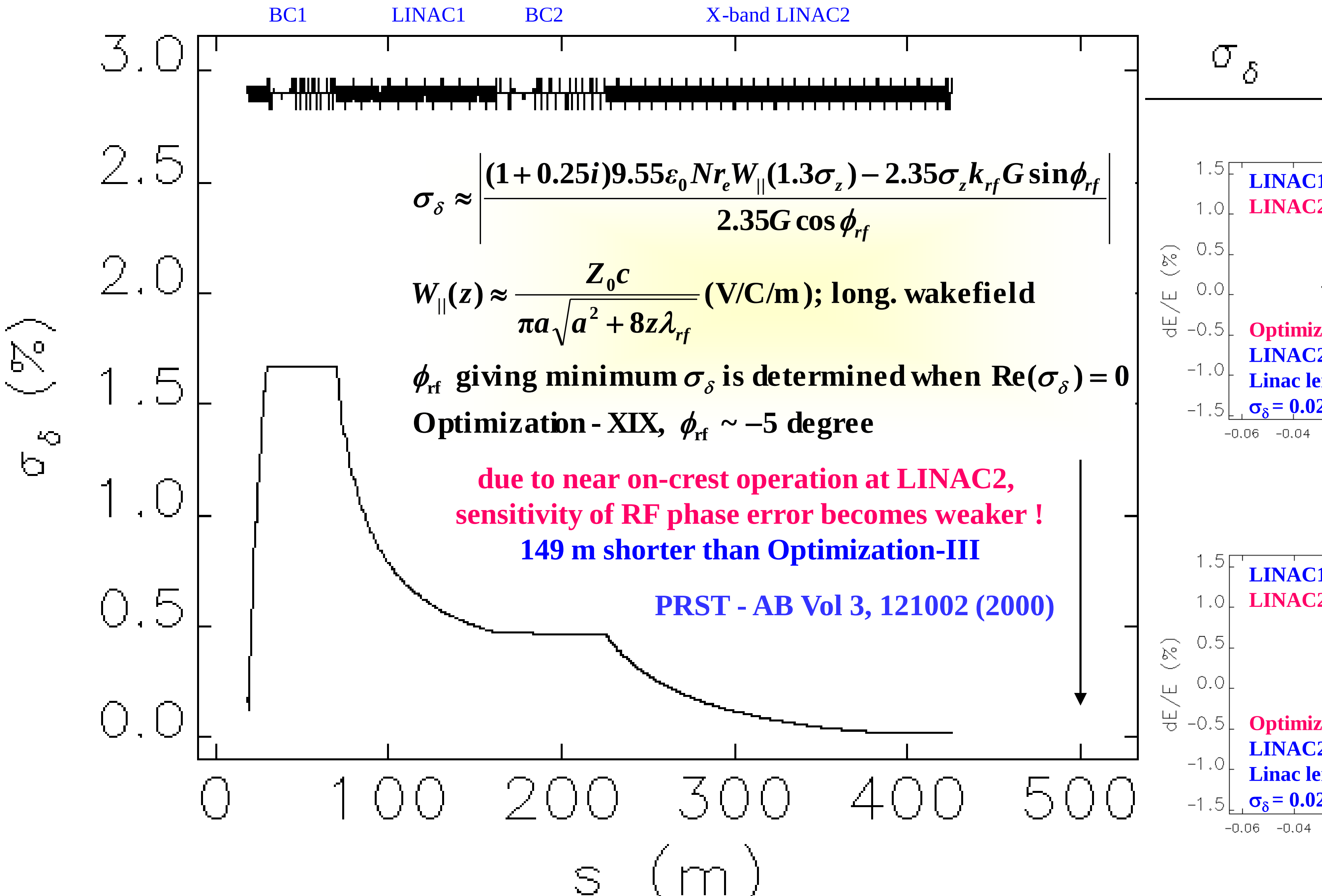
Optics for X-band Based LINAC2



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 ΔE ~ 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 !



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

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

ϕ_{rf} giving minimum σ_δ is determined when $\mathrm{Re}(\sigma_\delta) = 0$

Optimization-XIX, $\phi_{rf} \sim -5$ 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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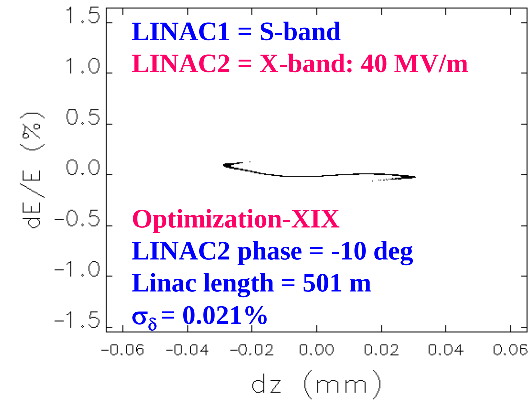
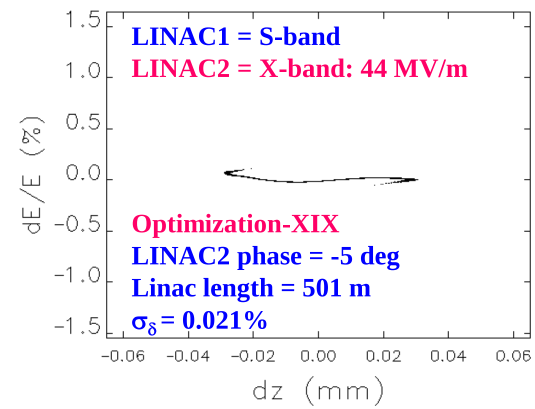
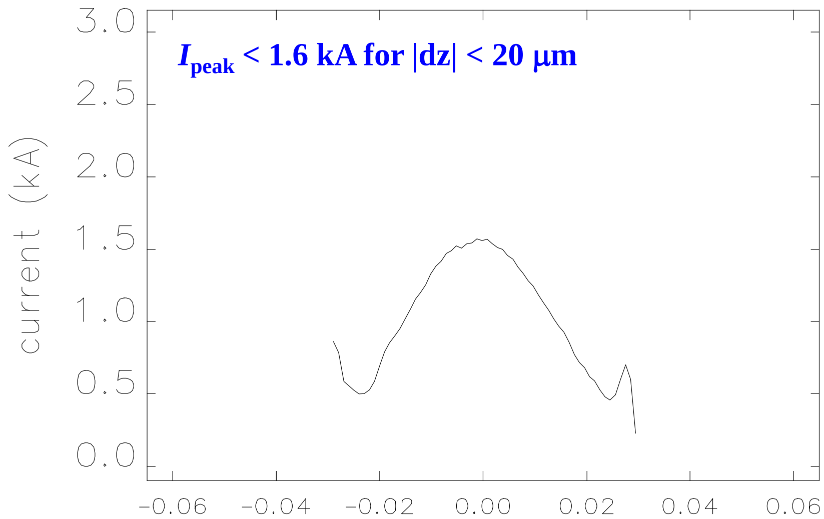
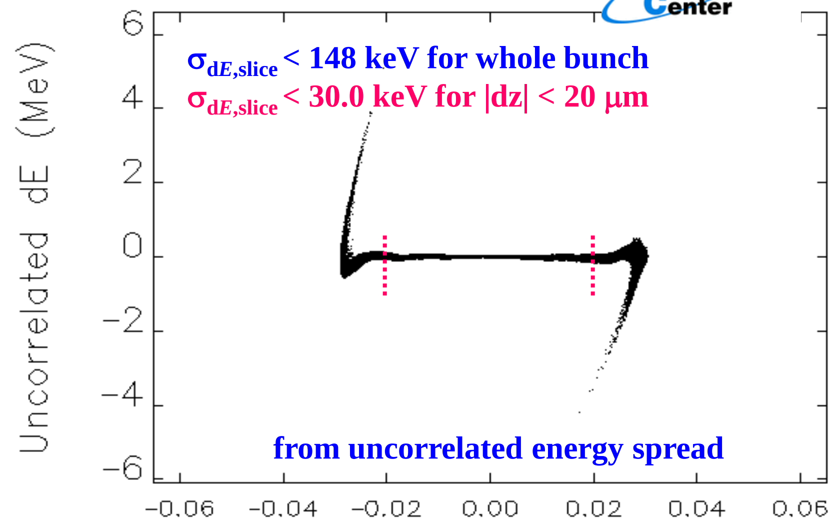


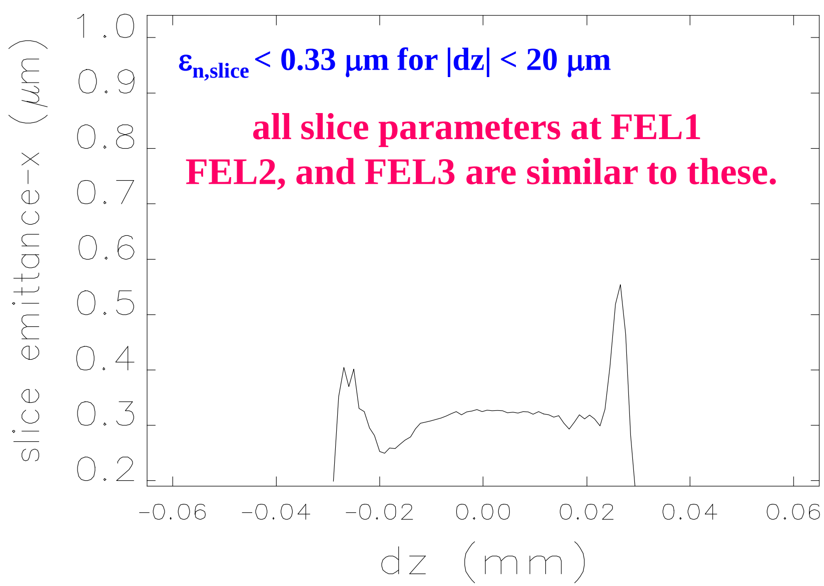


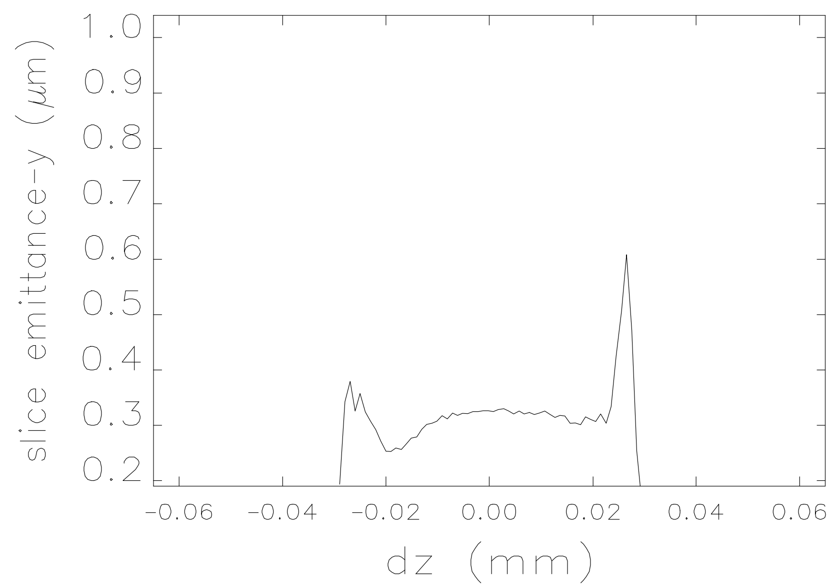
Performance of X-band based LINAC2



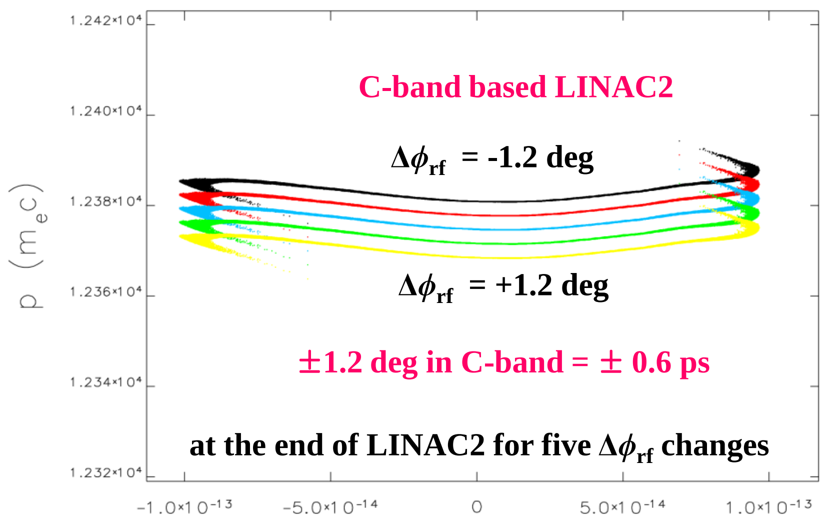


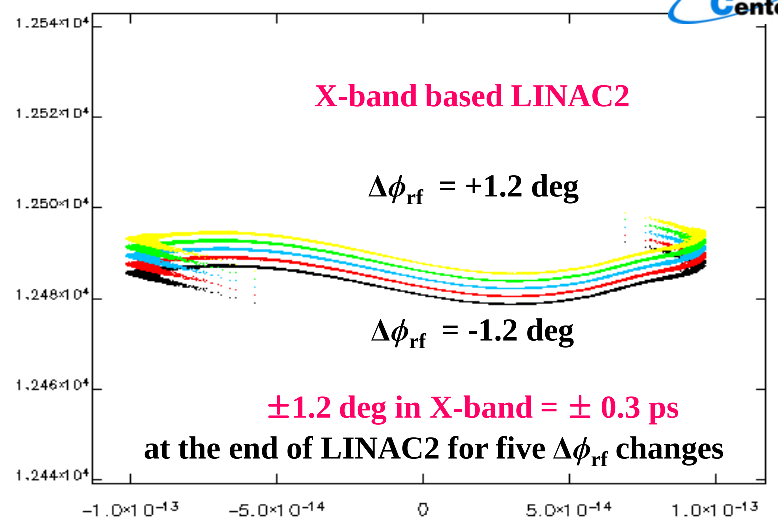
Slice Beam Parameters of Optimization-XIX is almost same as those of Optimization-III !





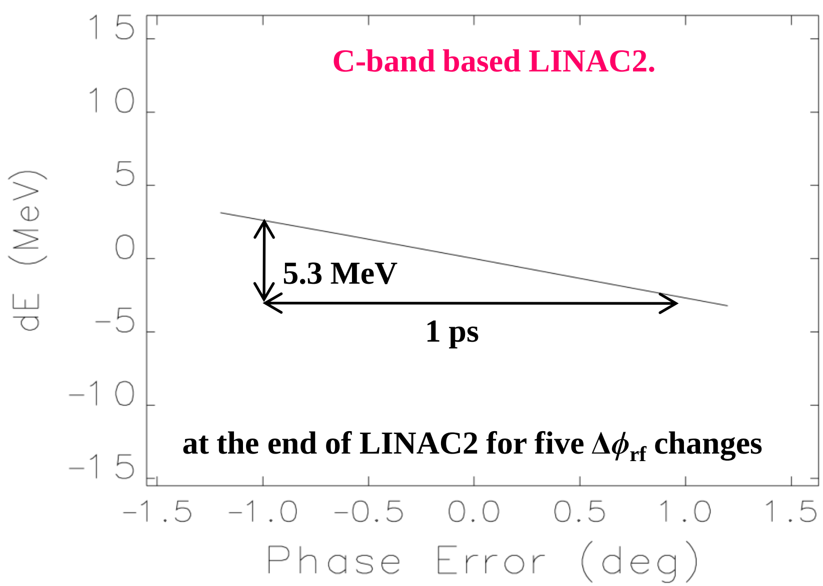
C-band & X-band LINAC2 - $\Delta\phi_{rf}$ Sensitivity

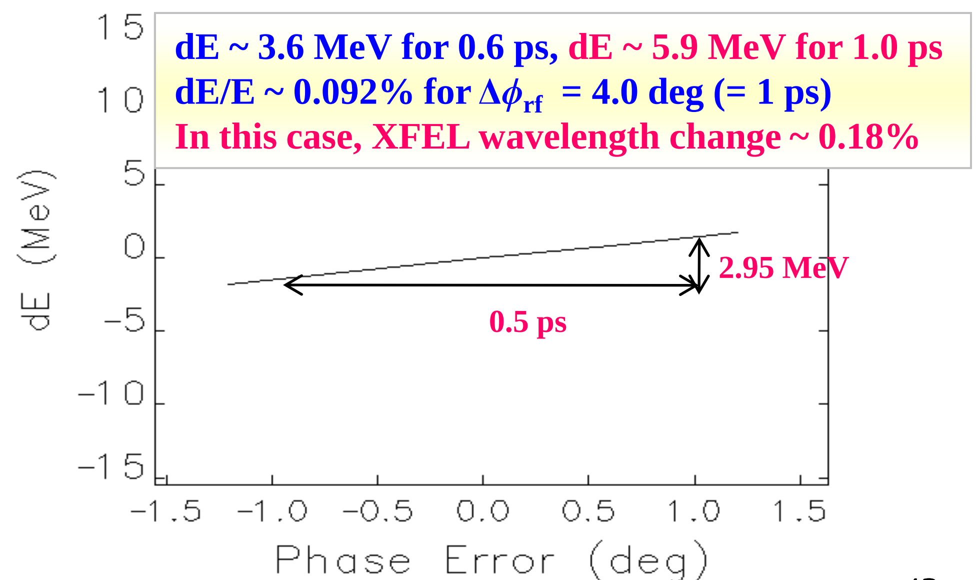




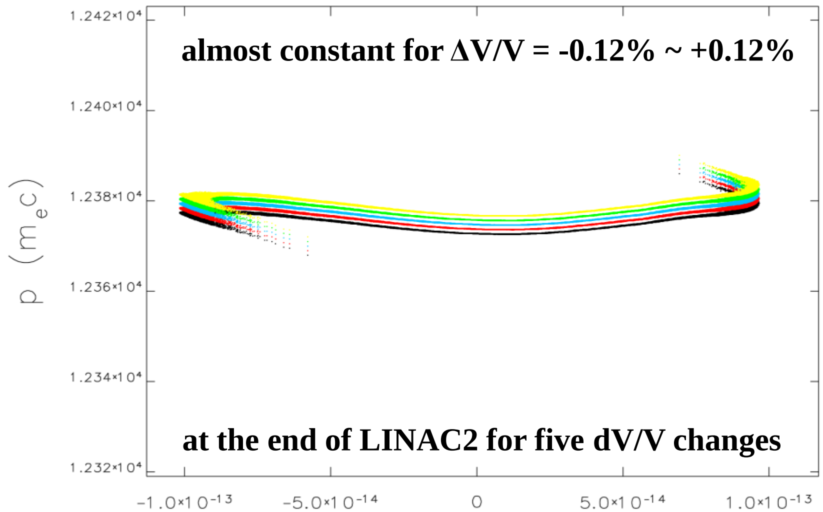
C-band Optimization-VI

X-band Optimization-XIX

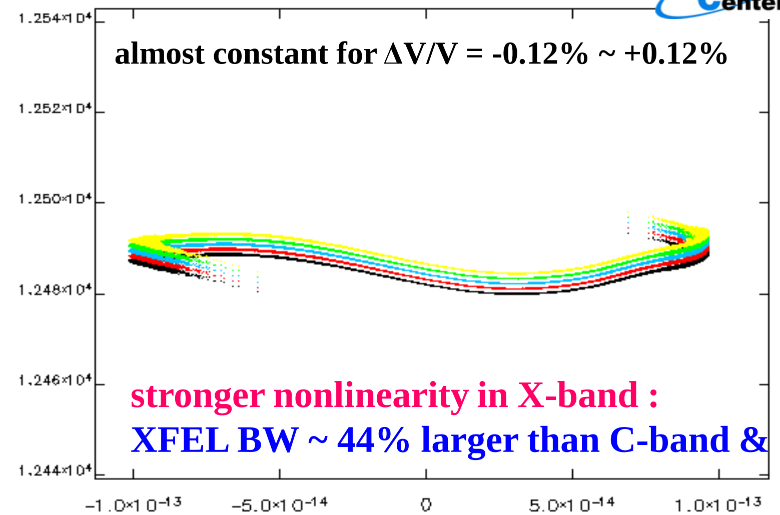




C-band and X-band LINAC2 - dV/V Sensitivity

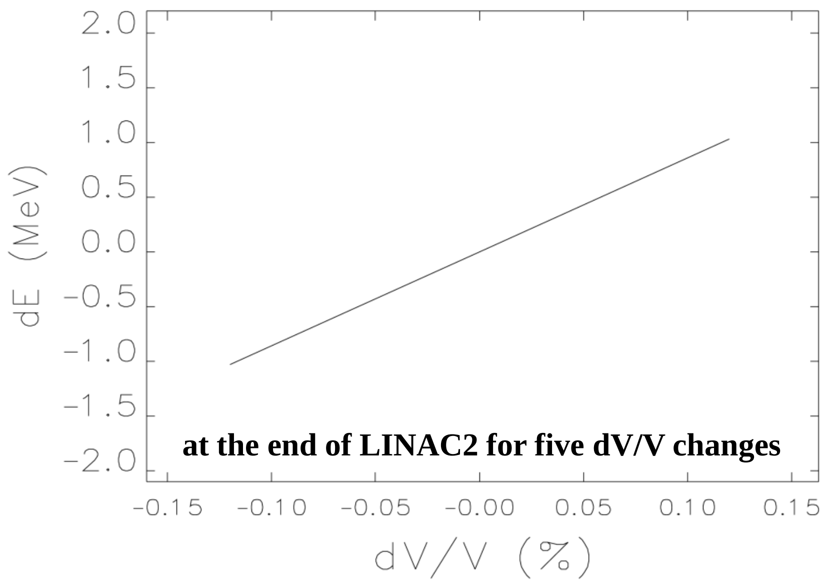


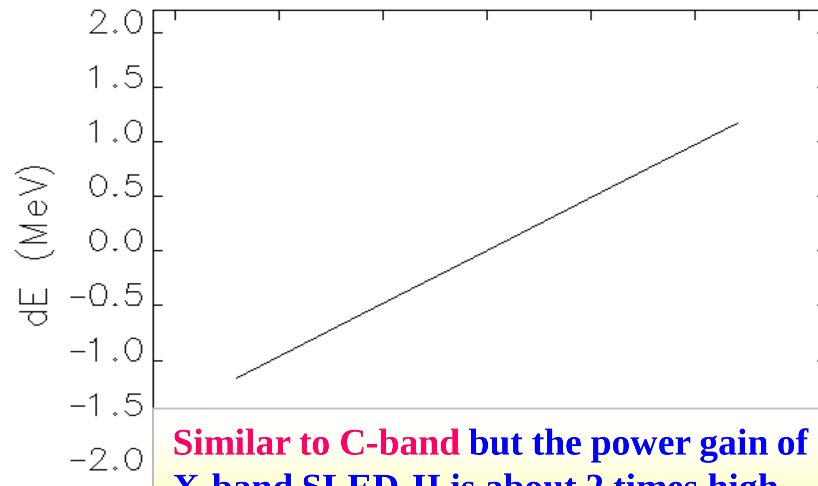
C-band Optimization-VI



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

X-band Optimization-XIX





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.

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.

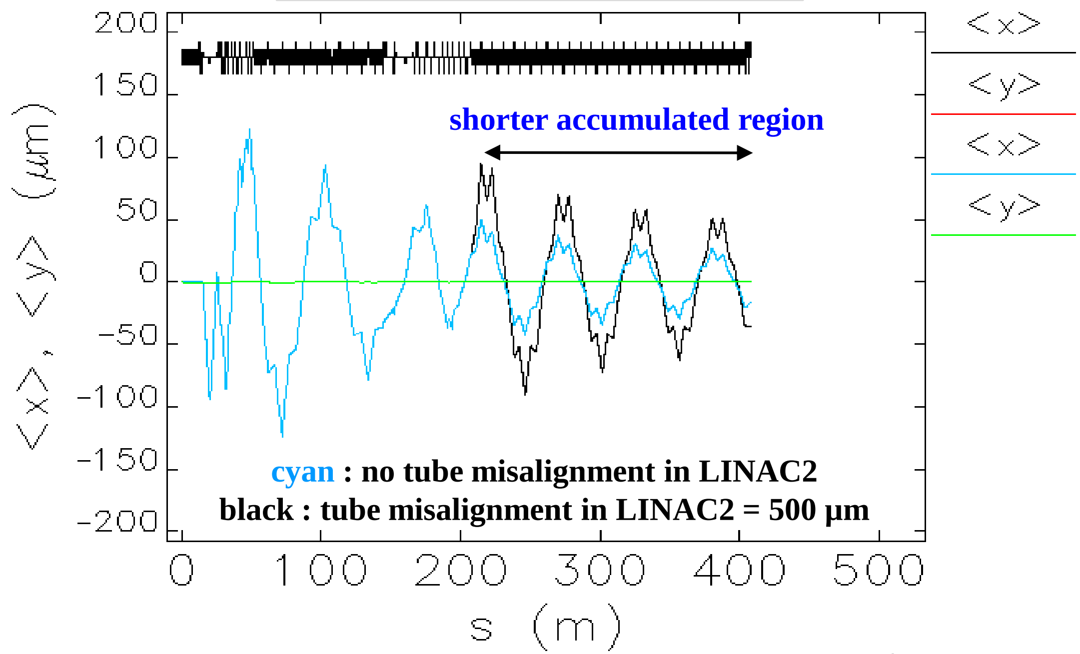
PRST - AB Vol 3, 121002 (2000) & LCLS-TN-01-1

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

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

If all 156 X-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 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 β-function and shorter X-band linac.

X-band Optimization-XIX



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PRST - AB Vol 3, 121002 (2000) & LCLS-TN-01-1

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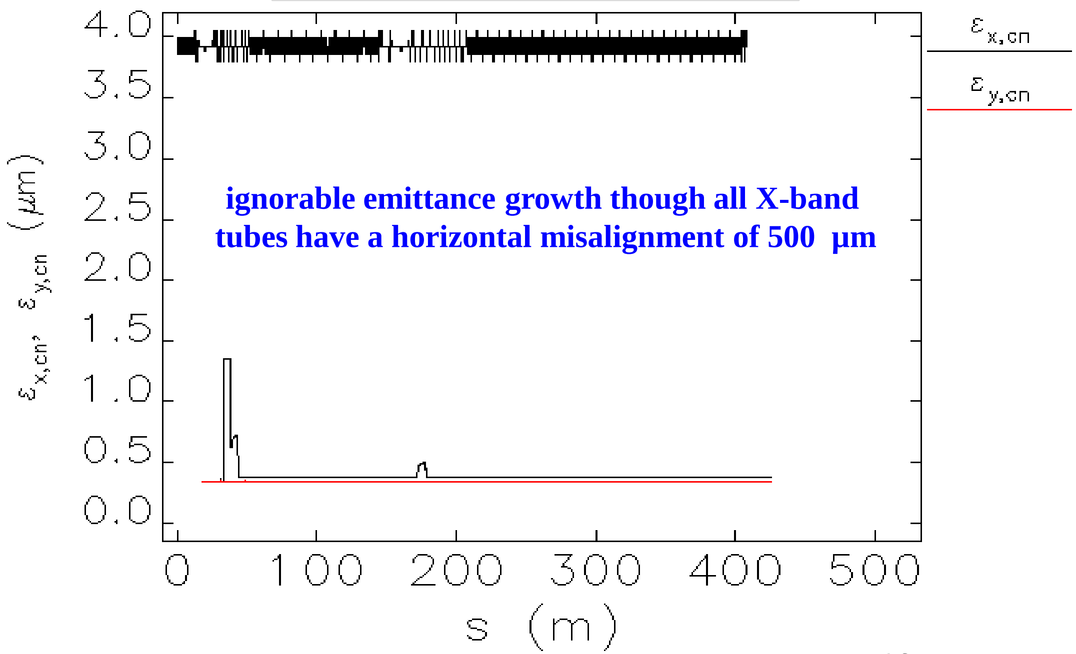
$$\frac{\varepsilon_0 + \Delta\varepsilon}{\varepsilon_0} \approx \sqrt{1 + \left(\frac{\pi r_e}{Z_0 c}\right)^2 \frac{N^2 \langle W_\perp \rangle^2 L^2 \beta}{\varepsilon_n \gamma} \Delta x^2}$$

Even though all 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:

$\Delta\varepsilon_{nx}$ ~ 0.005 μm, $\Delta\varepsilon_{ny}$ ~ 0.000 μm

Therefore, X-band tubes can be aligned with the normal alignment technology.

X-band Optimization-XIX



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.

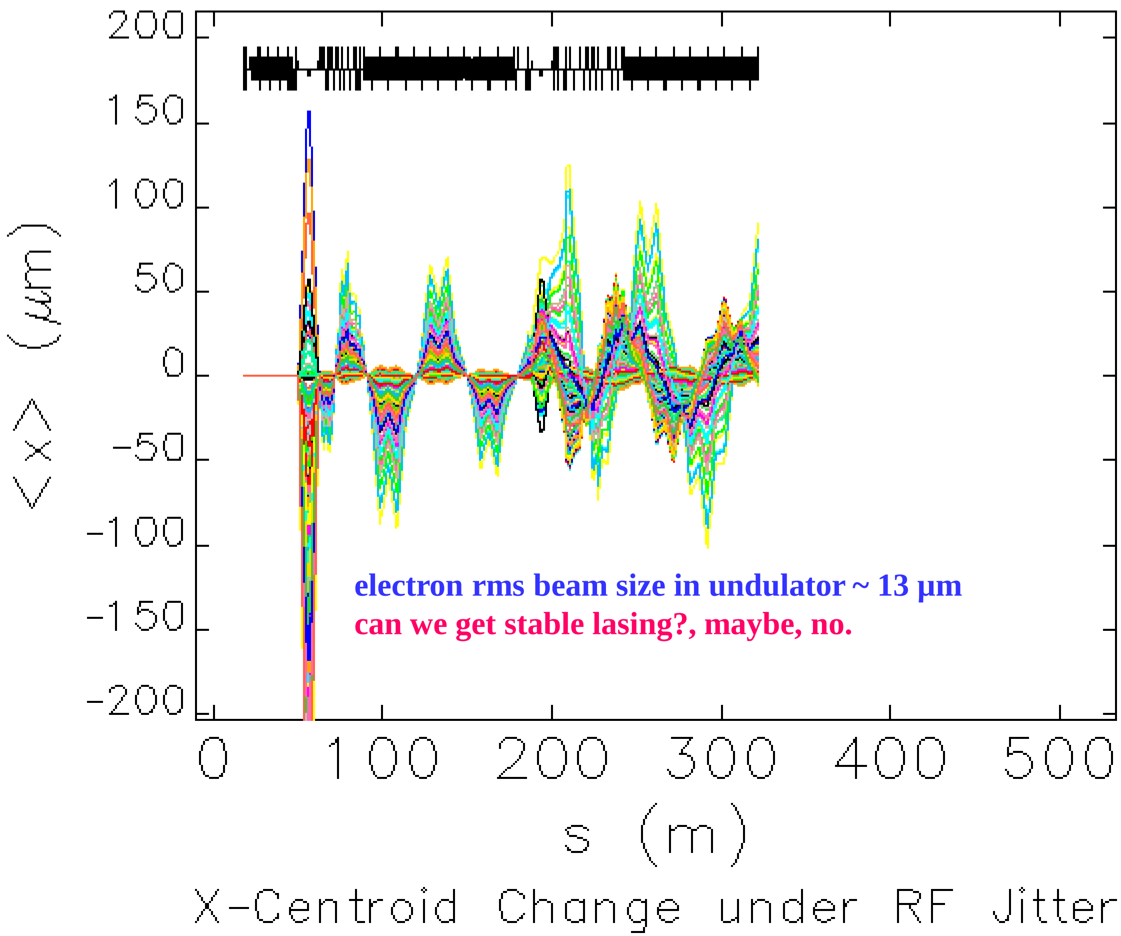
Summary

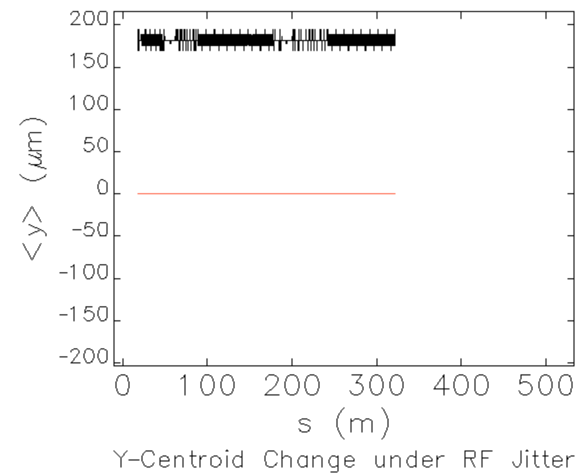
- We can control energy chirp effectively even at compact XFEL facilities by optimizing RF gradient, RF phase, and RF frequency, and linac length.
- In case of C-band and X-band linacs, RF phase jitter tolerance can be reduced by operating near on-crest RF phase.
- C-band and X-band can supply similar 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).

Appendix - Back Up Slides

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.



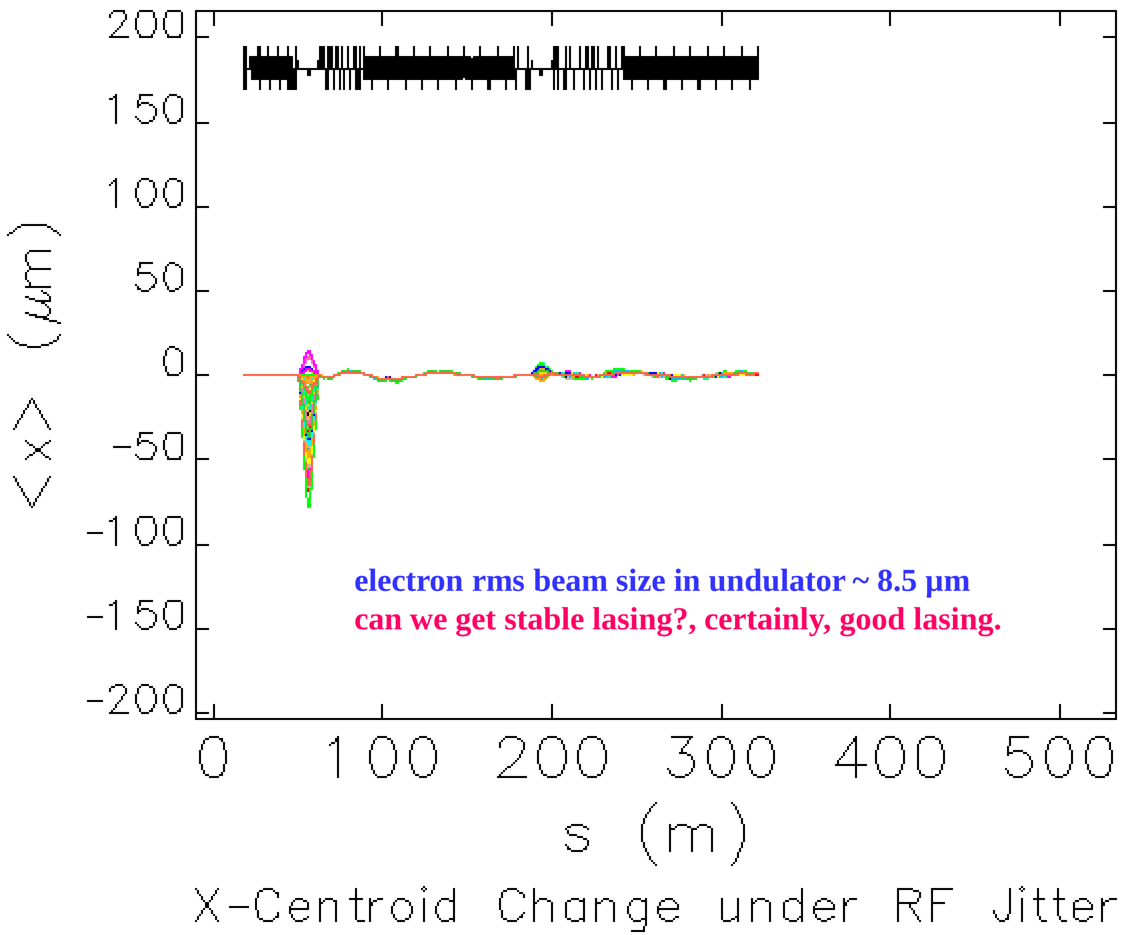


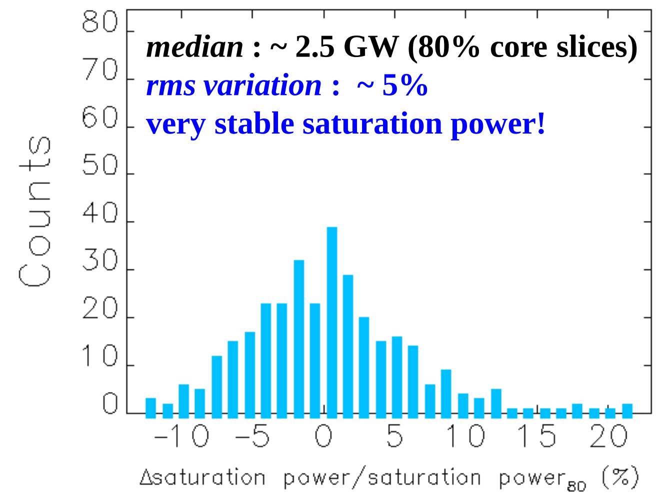
300 S2E simulations with RF Jitter Tolerances:

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)

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.

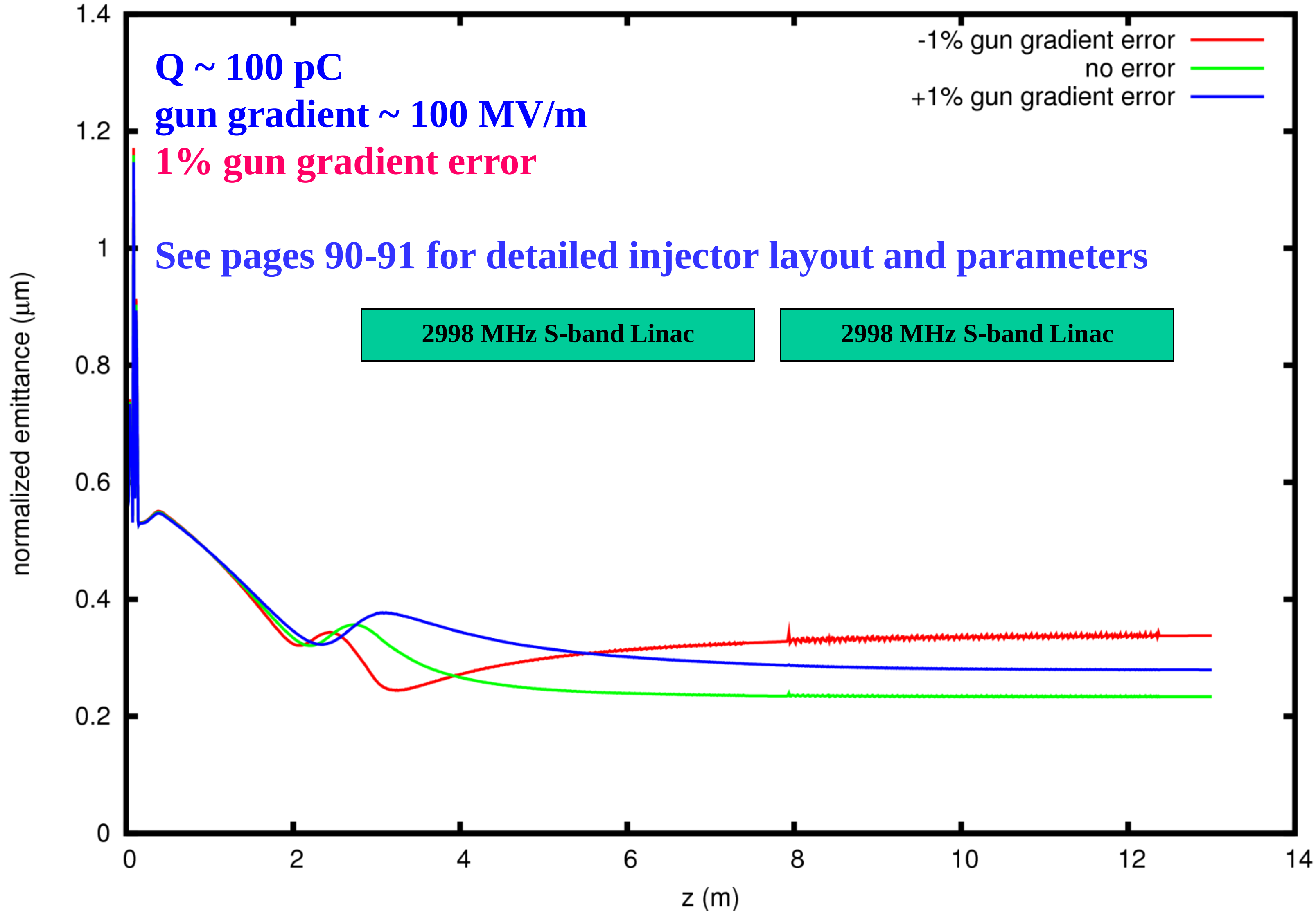




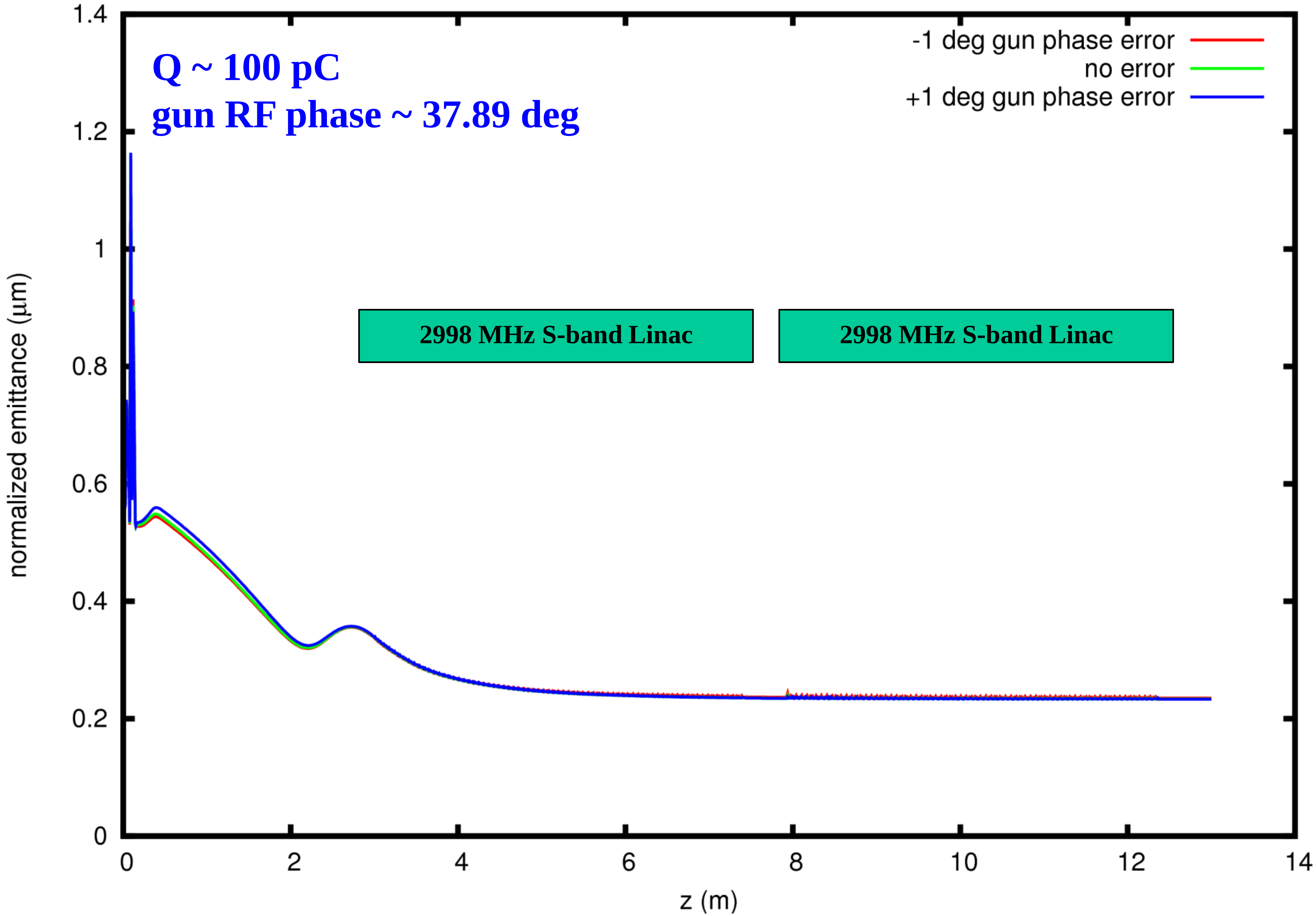
300 S2E simulations with Required Tolerances:

change error	≤ 1% (rms)
laser arrival timing error	≤ 1 fs (rms)
injector S-band RF phase error	≤ 0.005 deg (rms)
injector S-band RF voltage error	≤ 0.005% (rms)
injector X-band RF phase error	≤ 0.005deg (rms)
injector X-band RF voltage error	≤ 0.025% (rms)
BC power supply error	≤ 7.5 ppm (rms)

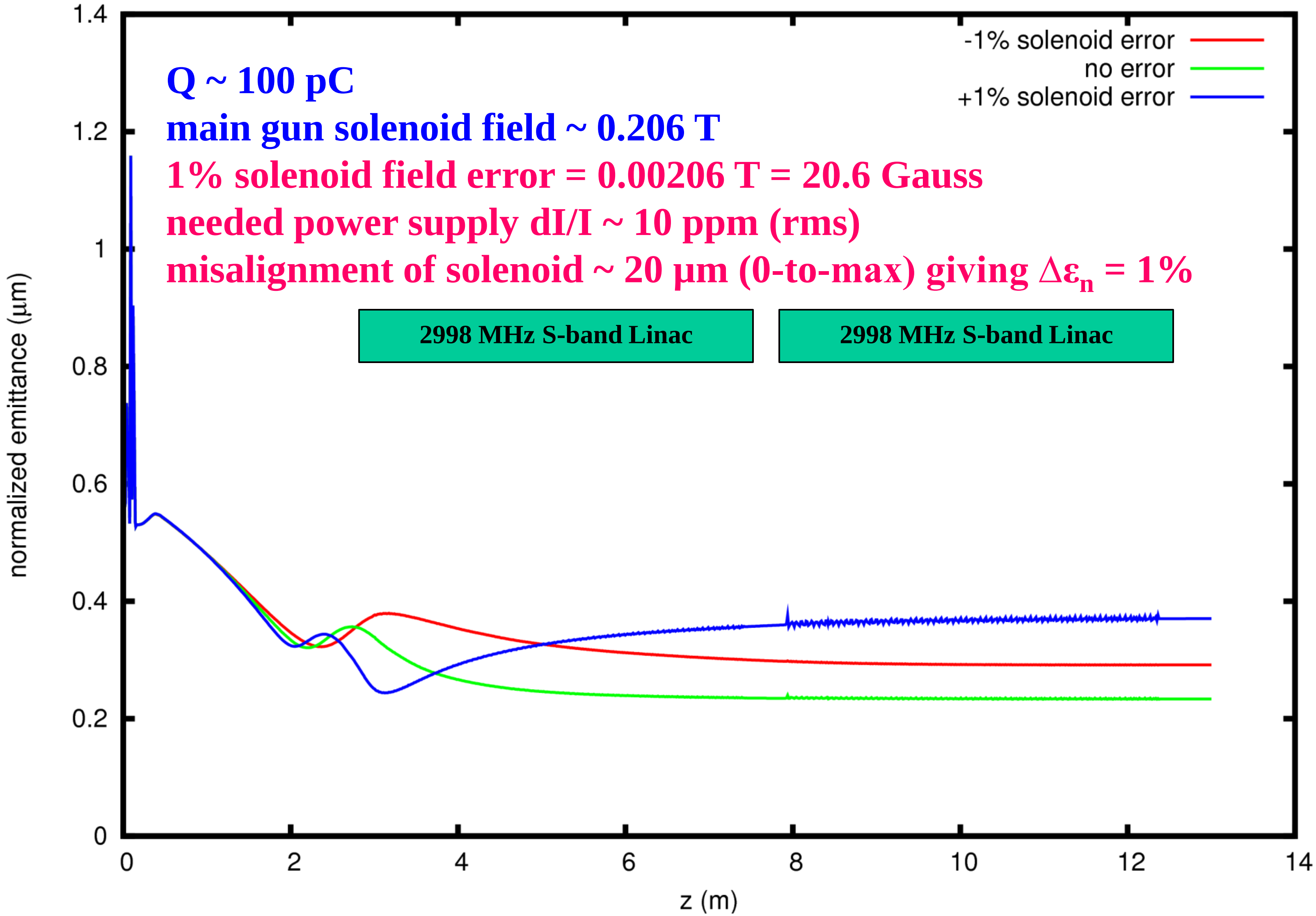
Other Difficulty Example - SwissFEL Injector



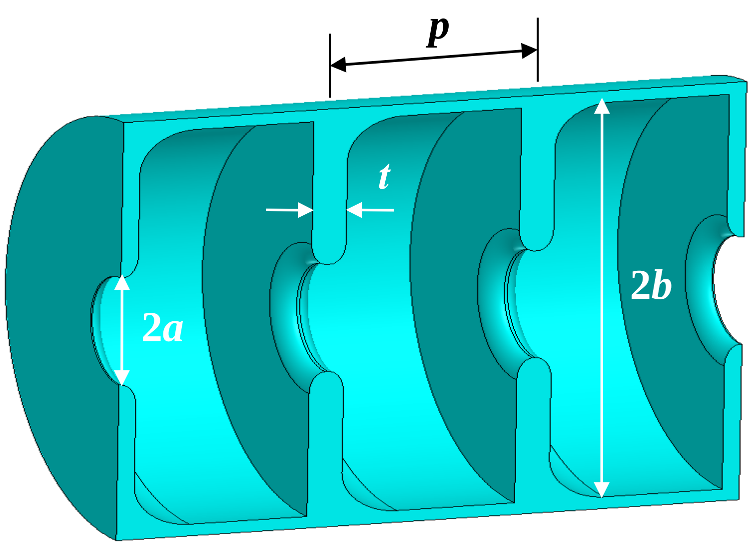
Other Difficulty Example - SwissFEL Injector



Other Difficulty Example - SwissFEL Injector



Wakefield of Two C-band Linac Structures



disk loaded type linac structure

MHI 2π/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 τ = 0.452
average shunt impedance = 69.5 MΩ/m
filling time = 222 ns
RF pulse length = 0.5 μs
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 3π/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 τ = 0.630
average shunt impedance = 66.1 MΩ/m
filling time = 333 ns
RF pulse length = 0.5 μs
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.

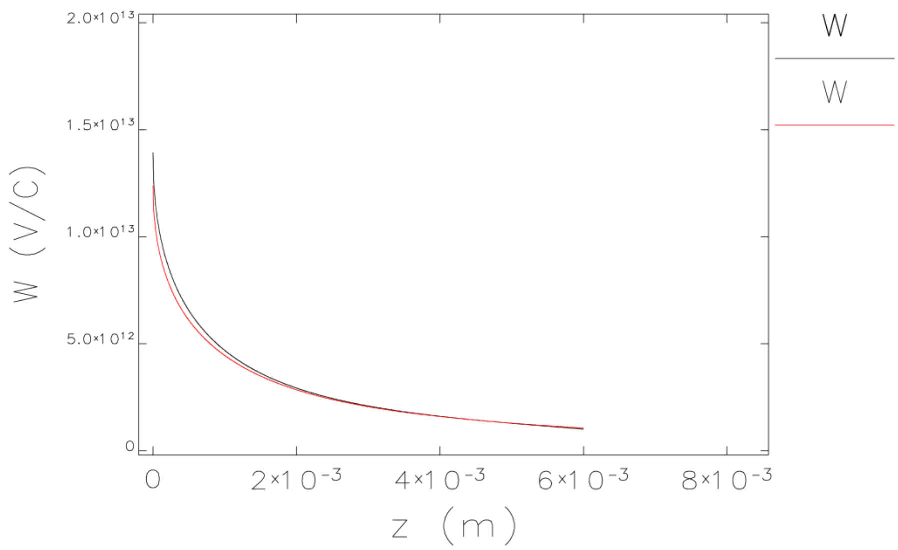
Short-Range Wakefields of Two C-band Structures

MHI 2π/3 Mode C-band Structure (red lines in plots below)

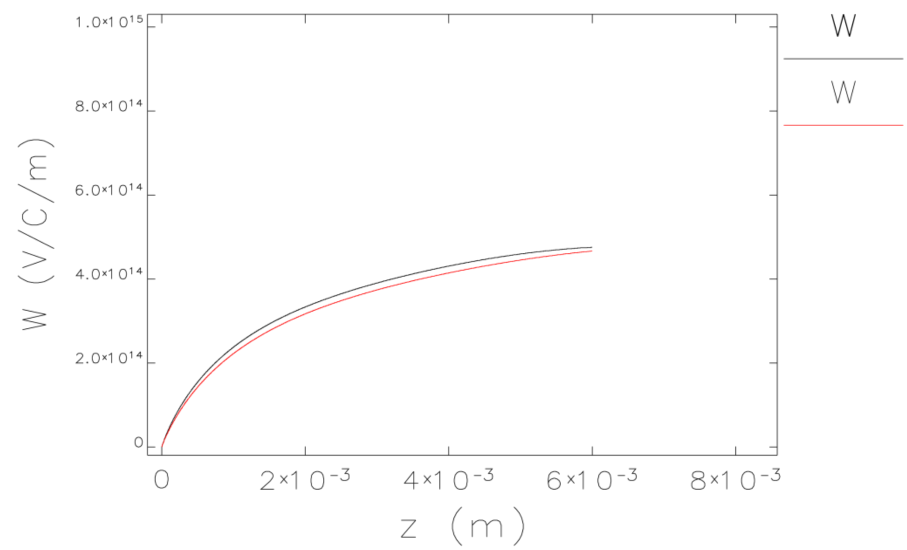
This structure is used for SwissFEL linac Optimization-XIV and Optimization-XV with RF Option-IV.

PSI 3π/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.



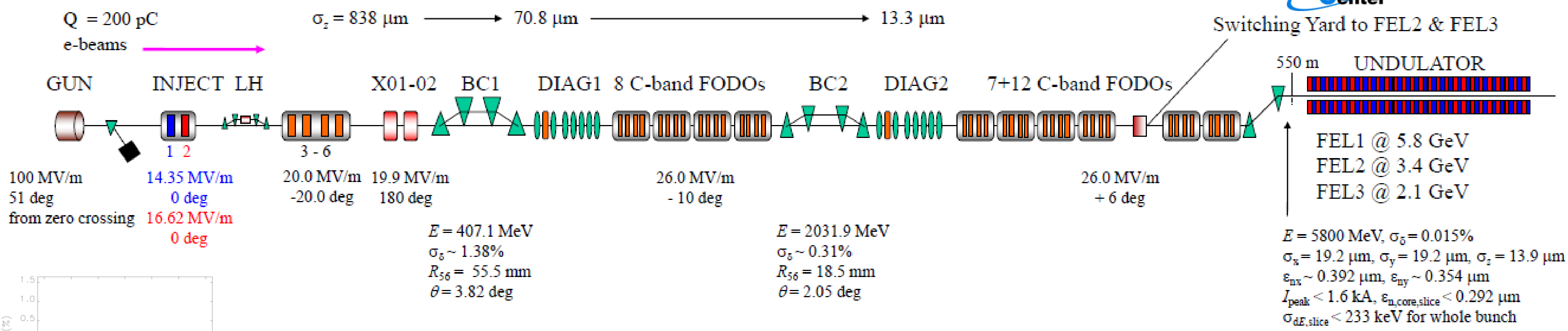
Long. Wakefield in C-band: 26 MV/m (black) & 28 MV/m (red)

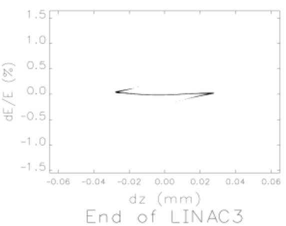


Trans. Wakefield in C-band: 26 MV/m (black) & 28 MV/m (red)

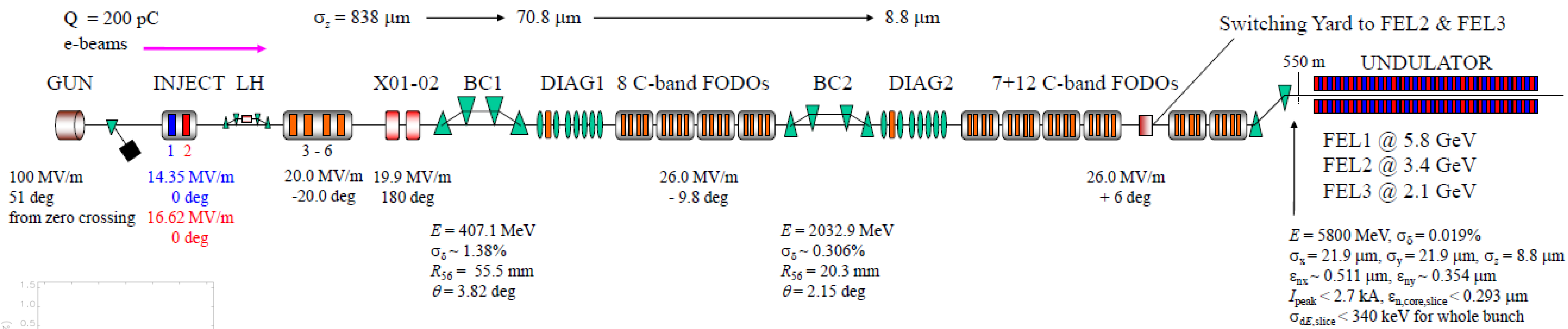
both structures have almost same short-range wakefields !

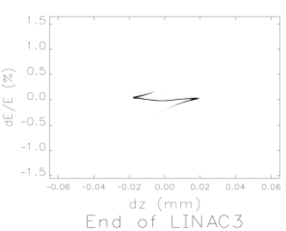
SwissFEL - Best Optimization with C-band LINAC1 & 2





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





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