Bunch Compression Scheme and Longitudinal Tolerances in SwissFEL

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+ SwissFEL

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Tolerance Goals

Arrival Time:

Characteristic scale is the electron bunch length of 20 fs rms. Arrival time jitter should be comparable or less than the bunch length

Beam Current / Bunch Length:

Average saturation power fluctuation of the SASE process set the scale for peak current stability. The goal is to stabilize the peak current on a level that it is on the same order as the intrinsic SASE fluctuations. This sets the requirements to the peak current stability to 5%.

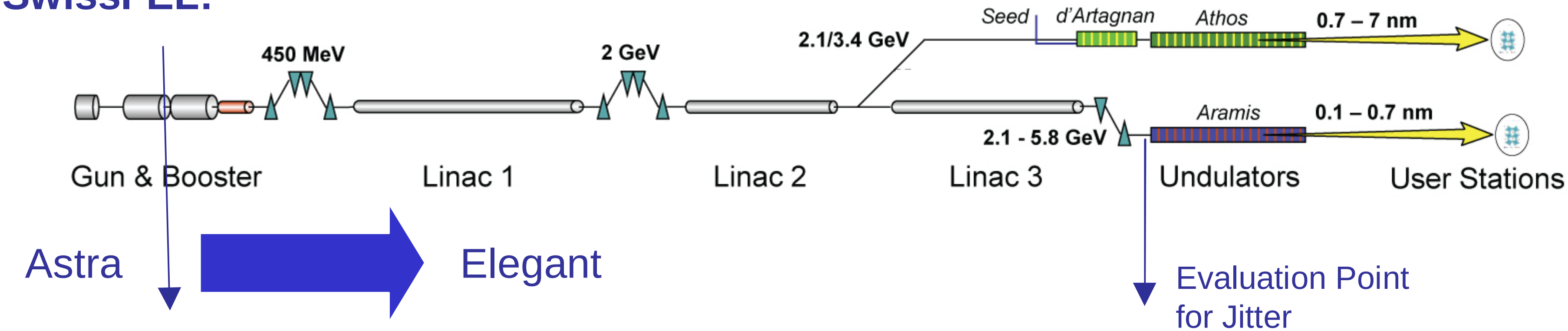
Beam Energy:

The FEL bandwidth is given by the FEL parameter and the smallest at one Angstrom with about 0.1%. 0.05% jitter in the mean energy would keep the resonant condition within the FEL bandwidth.

Simulation Strategy:

+ SwissFEL

SwissFEL:



- Study done with Elegant, starting at the laser heater.
- Fluctuation in electron beam parameters (arrival time and mean energy) as jitter source
- Astra simulation of injector correlates final beam jitter with jitter (RF phases and amplitudes, laser arrival time).

- Dependence of arrival time, peak current, bunch length and energy by collectively varying a single jitter source.
- Polynomial fit to dependence. **Linear term gives the sensitivity.**

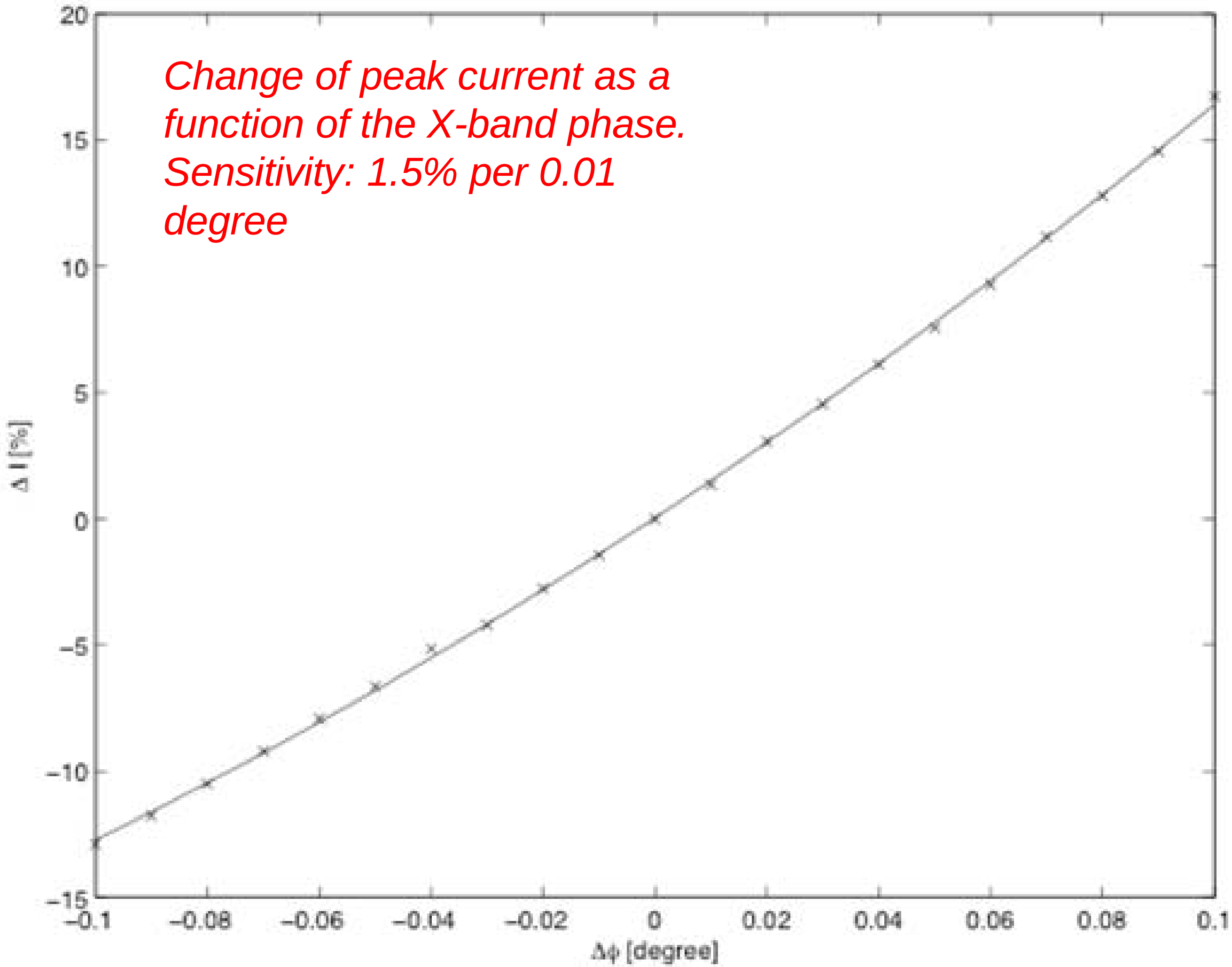
- Tolerances are derived from the sensitivity including the number of independent error sources. They describe how much a single parameter can jitter in order to reach the performance limits.

A little example *elegant* input

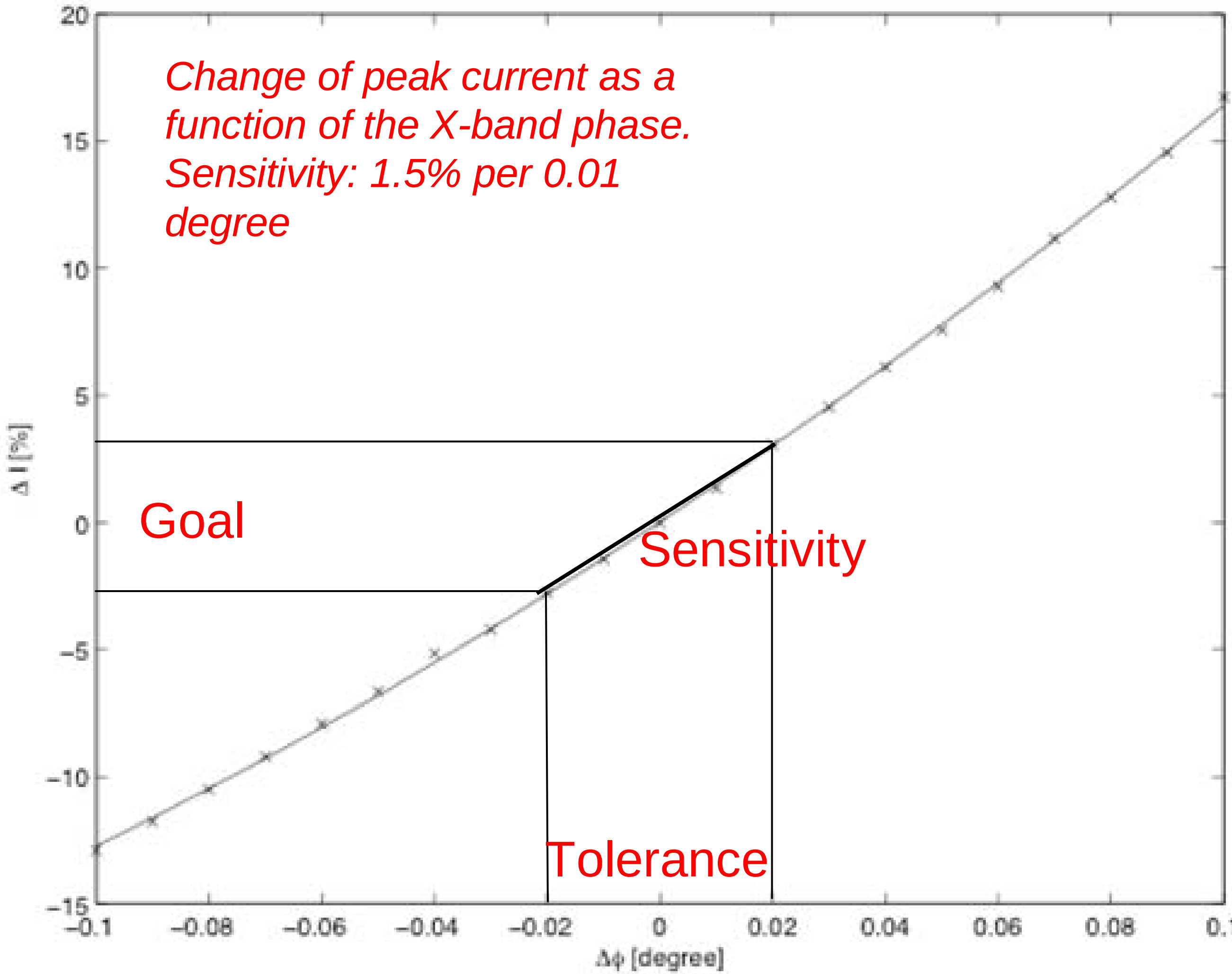
Example: s-band jitter

```
&run_control
        n_steps = 41,  reset_rf_for_each_step = 0
        first_is_fiducial = 1
&end

&error_control
        no_errors_for_first_step=1,  error_log=%s.erl
&end

&link_elements
    target = FINSB0[456].RACC01 ,     item = PHASE
    source = FINSB03.RACC01 ,     equation = "PHASE 1 *"
    mode = "static"
&end

&error_element
  name=FINSB03.RACC01,   item=PHASE,
  amplitude=0.1,   type="uniform"
&end
```

Sample Plot for Sensitivity



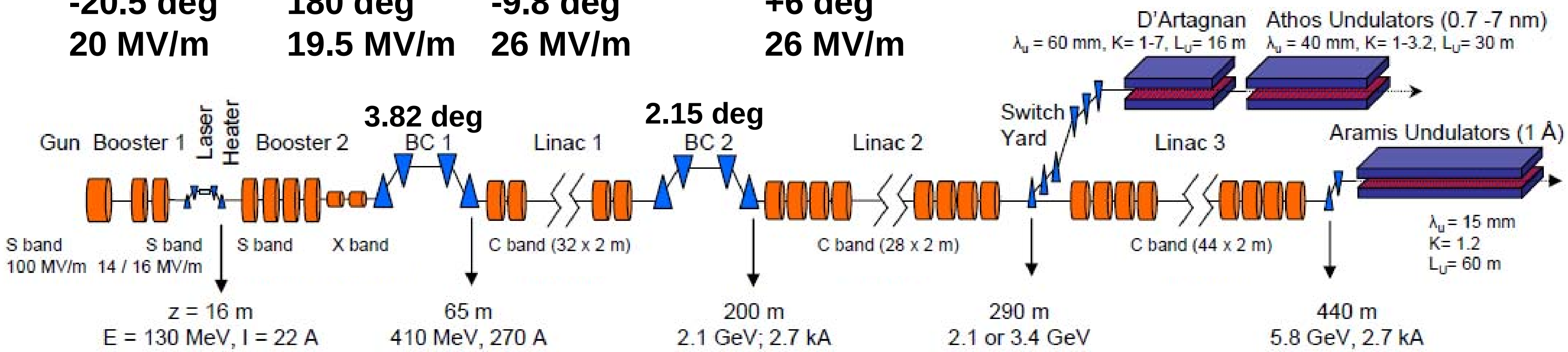
Sample Plot for Sensitivity



CDR SwissFEL Reference Design 200pC Layout

- This is the CDR reference design from which the tolerances were determined – recent changes are not included here
- Several modifications due to ongoing design of c-band RF structures – iris diameter => longitudinal wakes act on compression
- In this talk the focus is on the 200pC reference case

Booster 2:	X-Band:	Linac 1:	Linac 2/3:
-20.5 deg 20 MV/m	180 deg 19.5 MV/m	-9.8 deg 26 MV/m	+6 deg 26 MV/m



Tolerances CDR 200pC

+ SwissFEL

	arrival time [fs]	peak current [%]	energy [%]
goals:	20	5	0.05
S-Band Phase [deg]	0.062	0.022	0.404
S-Band Voltage [rel]	4.032 * 1e-004	1.758 * 1e-003	0.038
X-Band Phase [deg]	4.544	0.033	0.693
X-Band Voltage [rel]	2.114e-003	0.037	0.093
Linac 1 Phase [deg]	0.343	0.315	0.943
Linac 1 Voltage [rel]	1.034 * 1e-003	8.183 * 1e-003	3.255 * 1e-003
Linac 2 Phase [deg]	88.345	118.58	2.868
Linac 2 Voltage [rel]	0.157	0.150	5.260 * 1e-003
Linac 3 Phase [deg]	68.814	163.02	2.288
Linac 3 Voltage [rel]	0.122	0.1823	4.197e-003
Charge [pC]	16.099	1.685	151.04
initial arrival time [fs]	545.86	40.719	1.587 * 1e+004
Initial Energy [rel]	4.703 * 1e-004	3.691e-003	0.0178
BC1 angle [rel]	0.029	3.535 * 1e-004	7.471 * 1e-003
BC2 angle [rel]	2.401	2.698 * 1e-003	0.059

Expected Performance CDR 200pC

+ SwissFEL

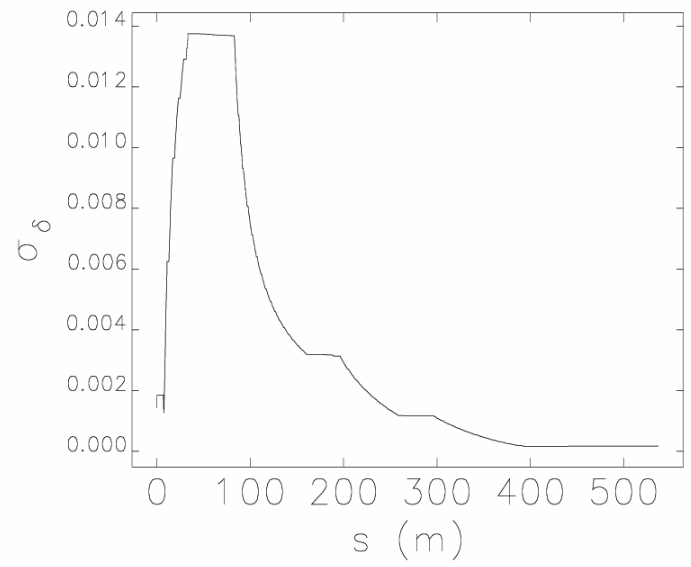
	arrival time [fs]	peak current [%]	energy [%]	Expected
S-Band Phase [deg]	4.836	3.389	1.858 * 1e-003	0.015
S-Band Voltage [rel]	5.953	0.341	1.580 * 1e-004	1.2 * 1e-004
X-Band Phase [deg]	0.264	9.066	4.326 * 1e-003	0.06
X-Band Voltage [rel]	1.135	0.016	6.444 * 1e-005	1.2 * 1e-004
Linac 1 Phase [deg]	1.750	0.476	1.591 * 1e-003	0.03
Linac 1 Voltage [rel]	2.322	0.073	1.843 * 1e-003	1.2 * 1e-004
Linac 2 Phase [deg]	6.791 * 1e-003	1.265 * 1e-003	5.231 * 1e-004	0.03
Linac 2 Voltage [rel]	0.015	4.006 * 1e-003	1.141 * 1e-003	1.2 * 1e-004
Linac 3 Phase [deg]	8.719 * 1e-003	9.202 * 1e-004	6.557 * 1e-004	0.03
Linac 3 Voltage [rel]	0.020	3.291 * 1e-003	1.430 * 1e-003	1.2 * 1e-004
Charge [pC]	2.485	5.936	6.621 * 1e-004	2
initial arrival time [fs]	1.099	3.684	9.452 * 1e-005	30
Initial Energy [rel]	4.253	0.135	2.812 * 1e-004	1e-004
BC1 angle [rel]	0.034	0.707	3.346 * 1e-004	5 * 1e-005
BC2 angle [rel]	4.164 * 1e-004	0.093	4.244 * 1e-005	5 * 1e-005
total	9.701	11.973	5.728 * 1e-003	

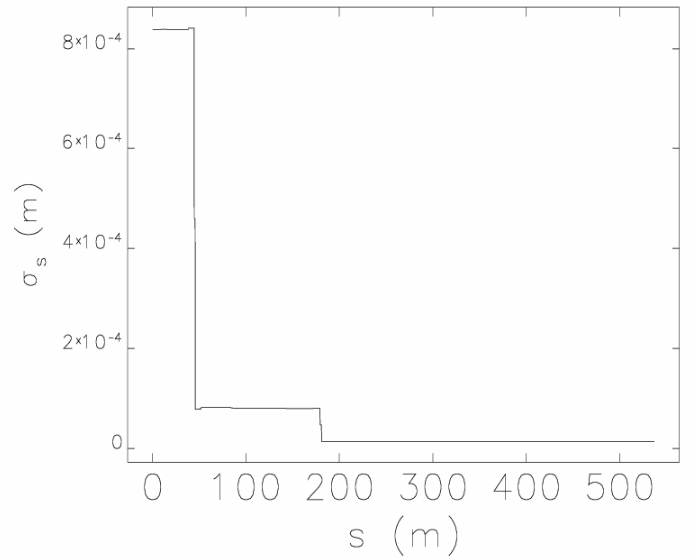
- Bunch compression in booth chicanes is controlled by the chirp in the Booster 2 section

  => phase jitter in Booster 2 affects compression in BC1 and BC2

  => phase tolerances in S-band booster are tight compared to downstream C-band linac 1.

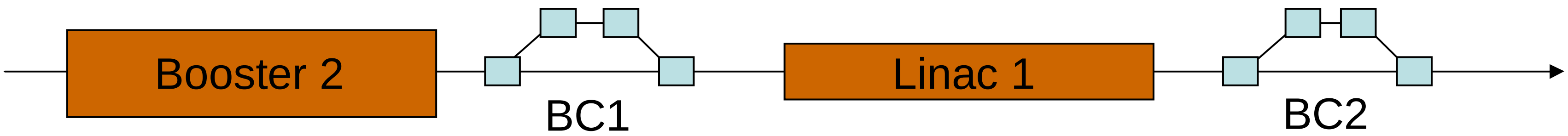
- A more equal distribution of chirp generation would lead to relaxed tolerances.

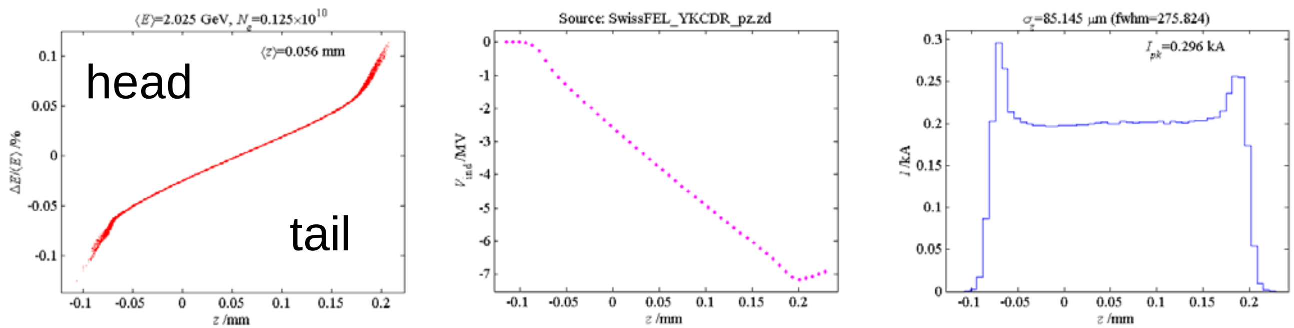




Optimised Layout 200pC Strategy

Energy chirp from booster is removed by longitudinal wakes in c-band linac. Additional chirp is generated in Linac 1 to control the compression in BC2.





Setup of such a scheme:

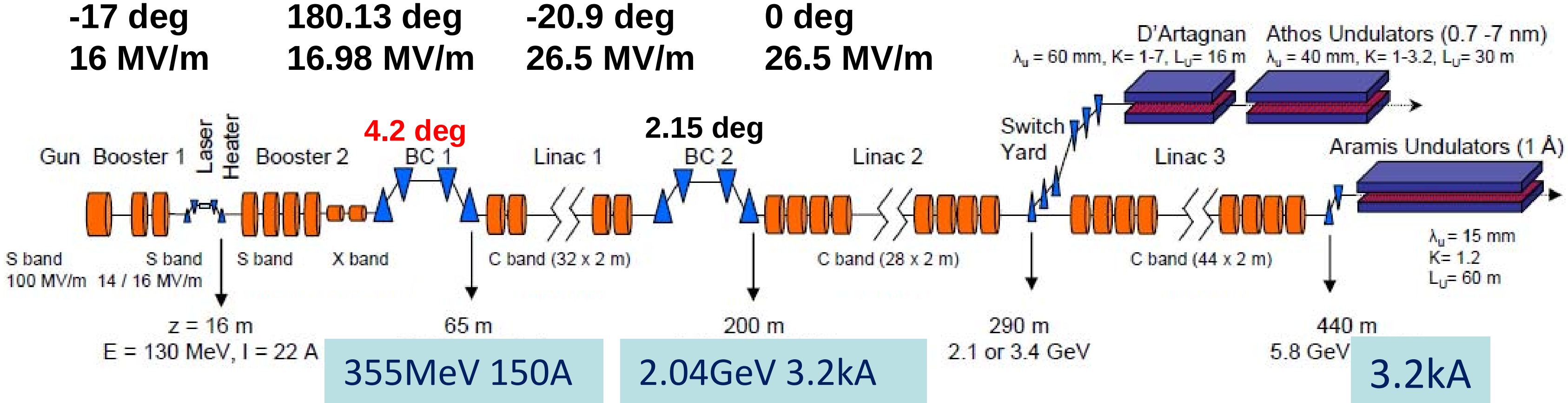
1. Set Linac 1 on crest.
2. Adjust Booster 2 phase to have minimal energy spread at BC2
3. Set Linac 1 phase to set bunch length after BC2
4. Adapt R_{56} in BC1 and BC2 and beam energy at the chicanes to set compression right – repeat 2.-4.

Optimised Layout 200pC Layout

Changes with respect to CDR 200pC design:

- Reduction of total chirp induced in the booster, partially compensated in terms of compression by reduction of energy at BC1 and higher bending angle
- Optimised longitudinal shaping by modified X-band parameters
- Stronger chirp induced in Linac 1
- Linac 2/3 set on crest – no active chirp control, slightly increased gradient to compensate for lower gradient upstream

Booster 2:	X-Band:	Linac 1:	Linac 2/3:
-17 deg 16 MV/m	180.13 deg 16.98 MV/m	-20.9 deg 26.5 MV/m	0 deg 26.5 MV/m



Tolerances Optimised Layout

	arrival time [fs]	peak current [%]	energy [%]
goals:	20	5	0.05
S-Band Phase [deg]	0.189	0.227	0.317
S-Band Voltage [rel]	1.014e-003	2.595 * 1e-004	1.072 * 1e-003
X-Band Phase [deg]	29.542	0.0611	0.864
X-Band Voltage [rel]	5.084 * 1e-003	1.652 * 1e-003	5.816 * 1e-003
Linac 1 Phase [deg]	0.152	0.0841	0.429
Linac 1 Voltage [rel]	1.009 * 1e-003	4.138 * 1e-003	4.633 * 1e-003
Linac 2 Phase [deg]	5.243 * 1e+003	1.577e+002	2.238 * 1e+003
Linac 2 Voltage [rel]	0.154	0.8704	5.102 * 1e-003
Linac 3 Phase [deg]	4.622 * 1e+003	1.778 * 1e+002	2.946 * 1e+003
Linac 3 Voltage [rel]	0.121	0.193	4.0716 * 1e-003
Charge [pC]	19.180	1.855	47.476
initial arrival time [fs]	6.156 * 1e+002	68.423	2.920 * 1e+003
Initial Energy [rel]	9.668 * 1e-004	3.121 * 1e-004	1.106 * 1e-003
BC1 angle [rel]	0.052	1.064 * 1e-003	0.014
BC2 angle [rel]	0.186	1.129 * 1e-003	0.015

	arrival time [fs]	peak current [%]	energy [%]	Expected
S-Band Phase [deg]	1.583	0.330	2.365 * 1e-003	0.015
S-Band Voltage [rel]	2.366	2.312	5.598 * 1e-003	1.2 * 1e-004
X-Band Phase [deg]	0.041	4.910	3.472 * 1e-003	0.06
X-Band Voltage [rel]	0.472	0.363	1.032 * 1e-003	1.2 * 1e-004
Linac 1 Phase [deg]	3.956	1.783	3.496 * 1e-003	0.03
Linac 1 Voltage [rel]	2.378	0.145	1.295 * 1e-003	1.2 * 1e-004
Linac 2 Phase [deg]	1.144 * 1e-004	9.510 * 1e-004	6.702 * 1e-007	0.03
Linac 2 Voltage [rel]	0.016	6.894 * 1e-004	1.176 * 1e-003	1.2 * 1e-004
Linac 3 Phase [deg]	1.298 * 1e-004	8.439 * 1e-004	5.092 * 1e-007	0.03
Linac 3 Voltage [rel]	0.020	3.107e-003	1.474 * 1e-003	1.2 * 1e-004
Charge [pC]	2.086	5.390	2.106 * 1e-003	2
initial arrival time [fs]	0.975	2.192	5.138 * 1e-004	30
Initial Energy [rel]	2.069	1.602	4.521 * 1e-003	1e-004
BC1 angle [rel]	0.019	0.235	1.773 * 1e-004	5 * 1e-005
BC2 angle [rel]	5.378 * 1e-003	0.221	1.620 * 1e-004	5 * 1e-005
total	6.262	8.332	9.628e-003	

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Tolerance Comparison

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- The tolerances on the s-band phases are relaxed by an order of magnitude and by a factor 2 for the x-band phase

- Requirements on the c-band linac 1 phase are tighter. But is still more relaxed then the initial s-band requirements.

Tolerances:

	optimised	CDR Design
S-Band Phase [deg]	0.189	0.022
S-Band Voltage [rel]	2.595 * 1e-004	4.032e-004
X-Band Phase [deg]	0.061	0.033
X-Band Voltage [rel]	1.652 * 1e-003	0.037
Linac 1 Phase [deg]	0.084	0.315
Linac 1 Voltage [rel]	1.009 * 1e-003	1.034e-003
Linac 2 Phase [deg]	1.577 * 1e+002	2.868
Linac 2 Voltage [rel]	5.102 * 1e-003	5.260e-003
Linac 3 Phase [deg]	1.778 * 1e+002	2.288
Linac 3 Voltage [rel]	4.072 * 1e-003	0.122
Charge [pC]	1.855	1.685
initial arrival time [fs]	68.423	40.719
Initial Energy [rel]	3.121 * 1e-004	4.703e-004
BC1 angle [rel]	1.064 * 1e-003	3.535e-004
BC2 angle [rel]	1.129 * 1e-003	2.698e-003

Expected Performance:

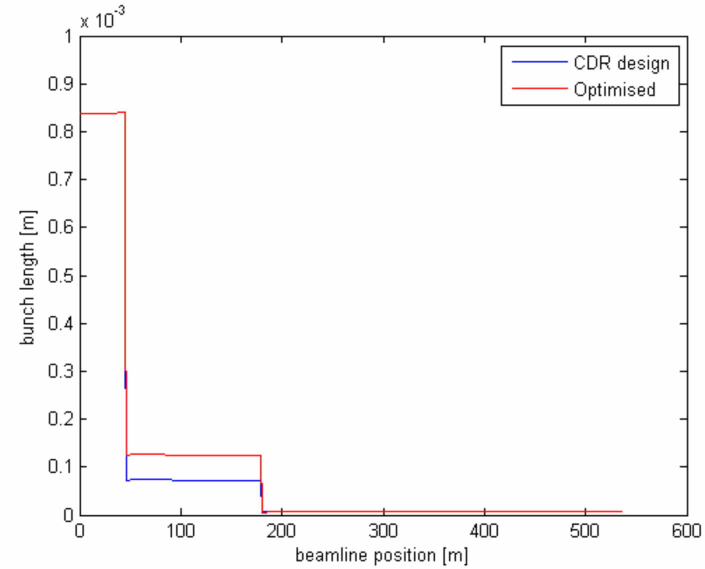
	Arrival Time [fs]	Peak Current [%]	Energy Jitter [%]
Tolerance Goal	**20**	**5**	**0.05**
CDR Design	9.70	11.97	0.00573
Optimised	6.26	8.33	0.00962

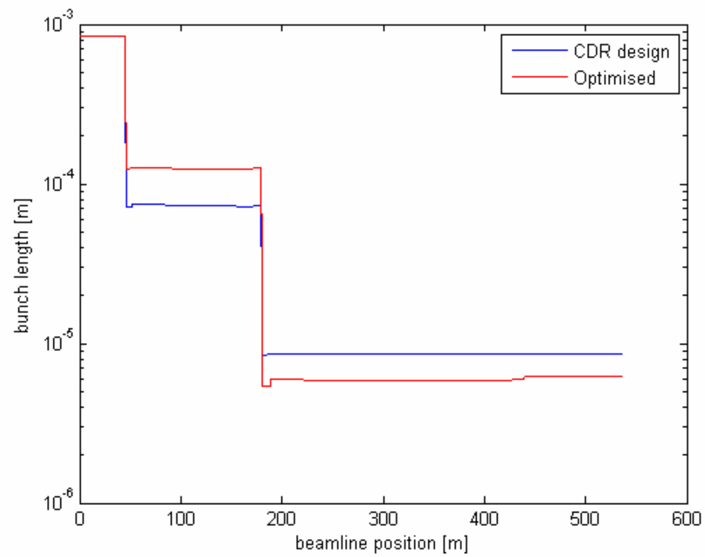
Compression Comparison

- Compression factors in CDR design:
  BC1: 11.54
  BC2: 8.41
- Bunch length:
  838.6 um → 72.68 um → 8.648 um

- Compression factors in Optimised design:
  BC1: 6.75
  BC2: 20.10
- Bunch length:
  838.6 um → 124.2 um → 6.178 um

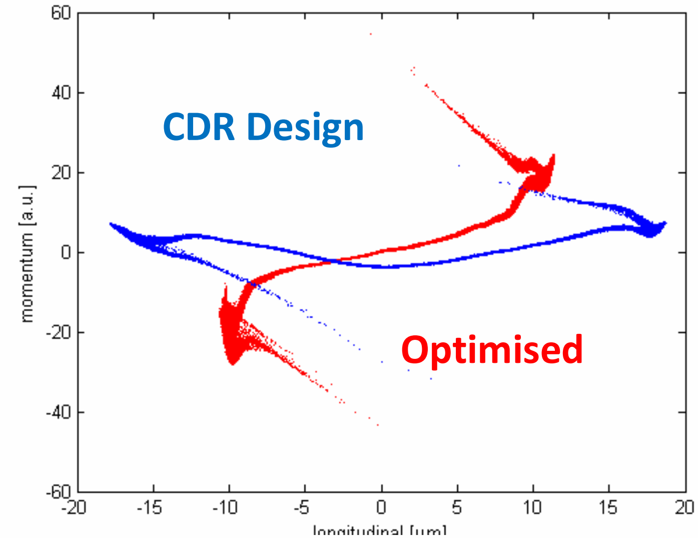
- Compression is Shifted from BC1 to BC2 with new chirp generated in Linac1.

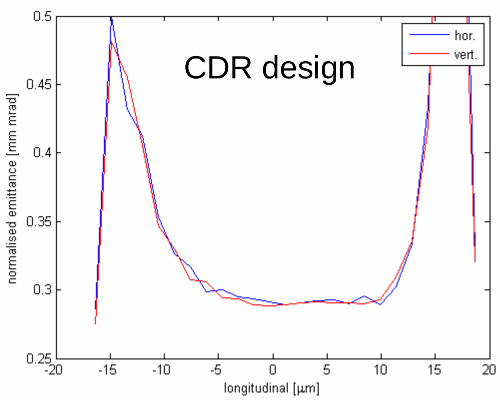


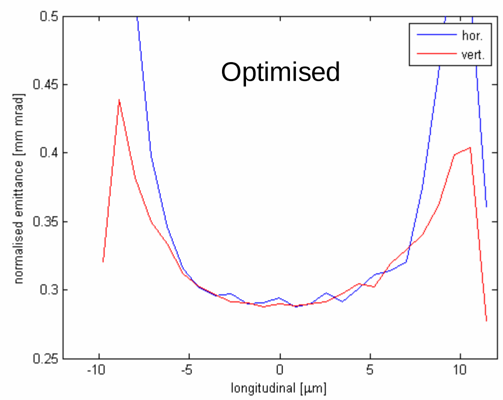


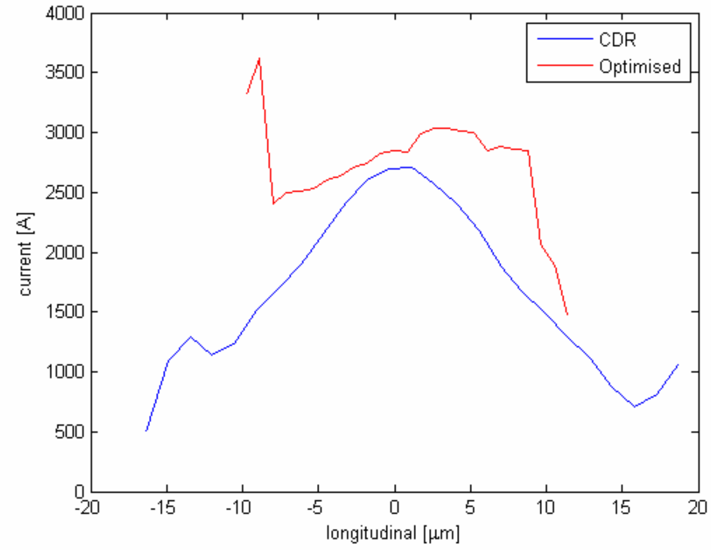
Beam Parameter Comparison

- Slice emittance is almost the same in both cases.
- Final energy chirp is smaller in the original design ➔ effects on bandwidth.
- Slightly higher peak current and wider peak current region in the Optimised design.

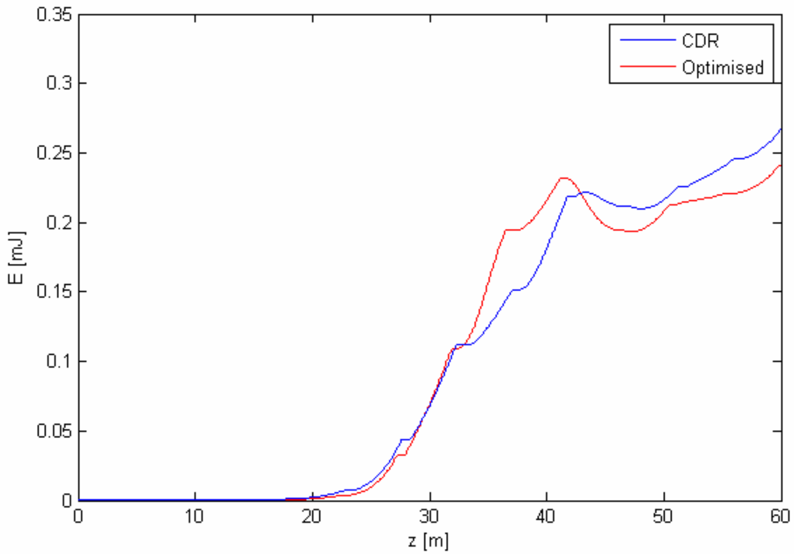


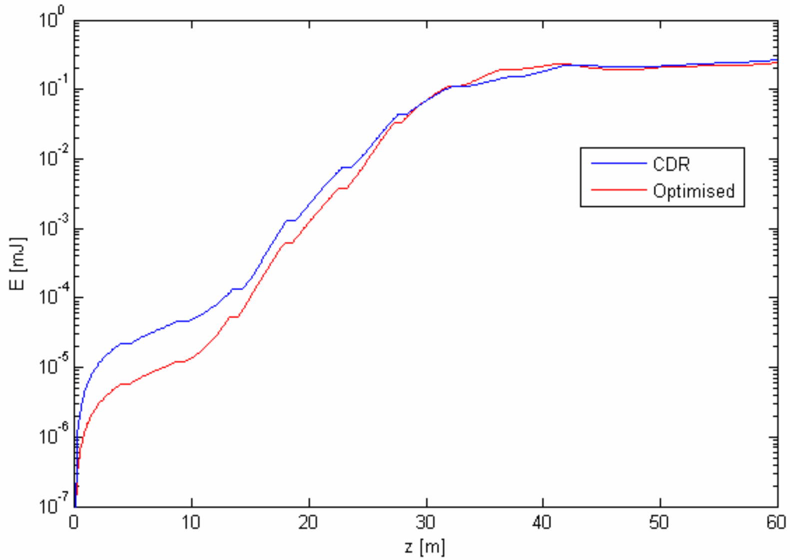






SASE Performance

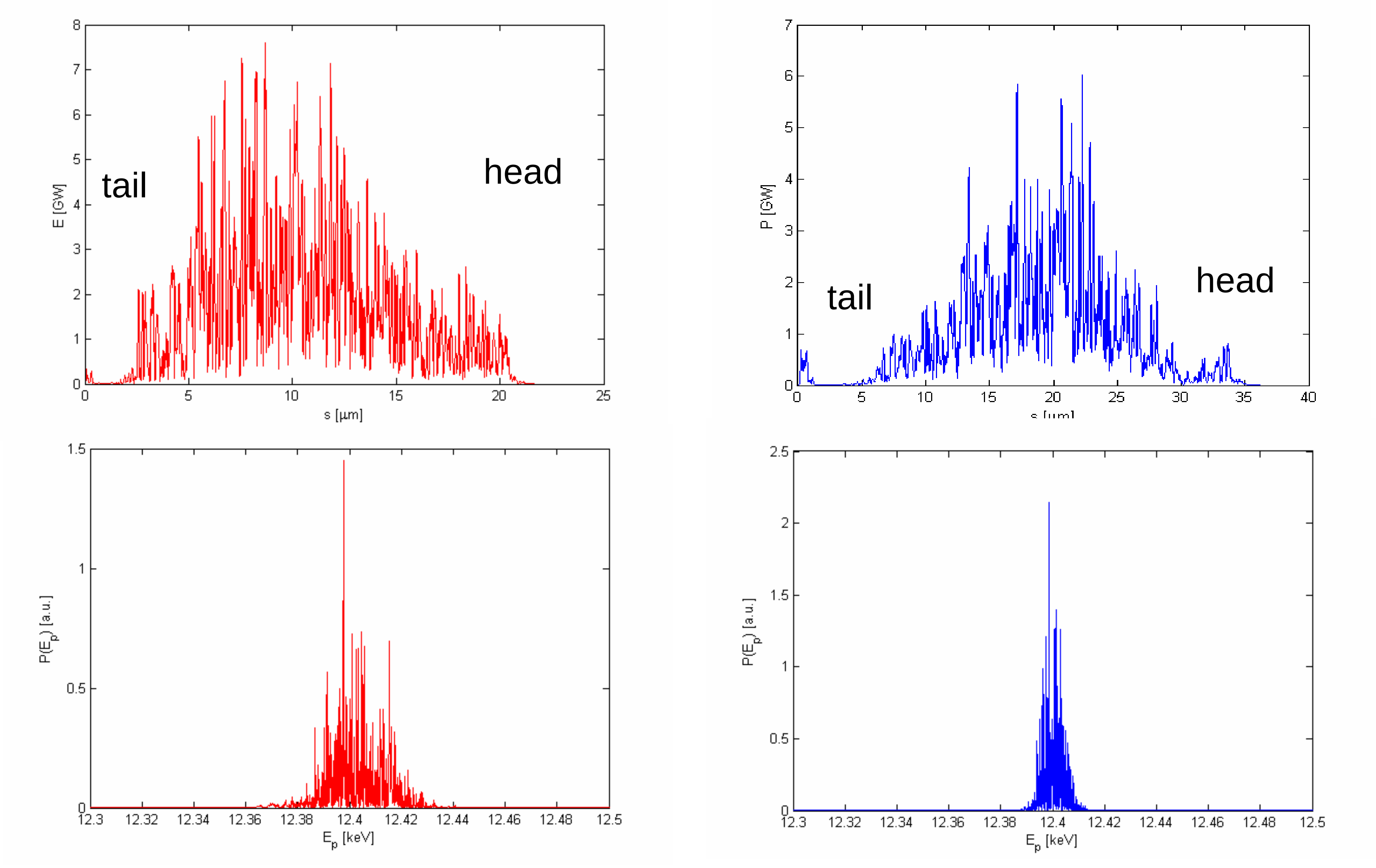




- SASE performance is similar in both cases.
- Due to the shorter electron bunch the FEL pulse is shorter.
- Since no chirp control was applied in Linac 2/3 the bandwidth is larger in the Optimised case.

	CDR	Optimised
Saturation	32 m	32 m
E_{sat}	0.11 mJ	0.11mJ
σ_p	20 fs	14.1 fs
$\langle P_{sat} \rangle$	2.1GW	3.1 GW
BW	0.065 %	0.095 %

SASE Performance



Summary and Outlook

- Different working points for the SwissFEL were presented, which share the same hardware
- An optimised design was presented which relax the tightest RF tolerances (S-band and X-band system) up to an order of magnitude by redistribution of the total bunch compression and optimises FEL photon parameters.

- Estimated beam performance is fulfils the requirements for arrival time and energy stability

- The tight beam based requirements on peak current stability are almost reached – however requirements from the users are more relaxed provided a photon pulse energy measurement on the percent level

Thank You

for Your

Attention!

- A little theory of machine jitter
  - Sensitivity S_j is the linear correlation between an error source j (with occurs N times) and the performance goal $\bar{\sigma}_A$.
  - The jitter of j σ_j contribute to the total jitter which has to fulfil:

$$\bar{\sigma}_A = \sqrt{\sum \frac{\sigma_j^2 S_j^2}{N}}$$

  - If j is allowed to use the whole budget for $\bar{\sigma}_A$ the tolerance is:

$$\bar{\sigma}_j = \frac{\bar{\sigma}_A \sqrt{N}}{S_j}$$

  - If more sources jitter the tolerances are effectively tighter: $\sigma_j = a_j \bar{\sigma}_j$
  - Since $\sqrt{\sum a_j^2 \bar{\sigma}_A^2} = \bar{\sigma}_A$ has to be fulfilled on gets for a_j: $\sum a_j^2 = 1$

In this study the sensitivities S_j and tolerances $\bar{\sigma}_j$ are determined. The total jitter using some expected performance values are compared with the goals.

Injector Sensitivities

Sensitivities from the gun to the laser heater are determined in ASTRA runs.

Tolerances defined in the previous elegant study are used as tolerance goals

Source	Parameter	Arrival Time	Bunch Length	Energy Jitter
Units		fs	fs	%
Laser time	fs	0.81339	6.2010e-05	-1.227e-05
Gun phase	deg	-1.7322e-04	0.0538	4.0445e-04
Gun gradient	rel	-0.0713	-2.3336	181.82
SB01 Phase	degree	3.2086e-04	0.0036	-0.0109
SB01 Volt	rel	-3.9045	-0.0278	44.1662
SB02 Phase	degree	6.1665e-05	1.2254e-04	-0.0111
SB02 Volt	rel	-0.1309	-2.7007e-04	51.0535
Bunch charge	rel	1.0365e-06	6.619e-04	-8.2495e-05

Injector Tolerances

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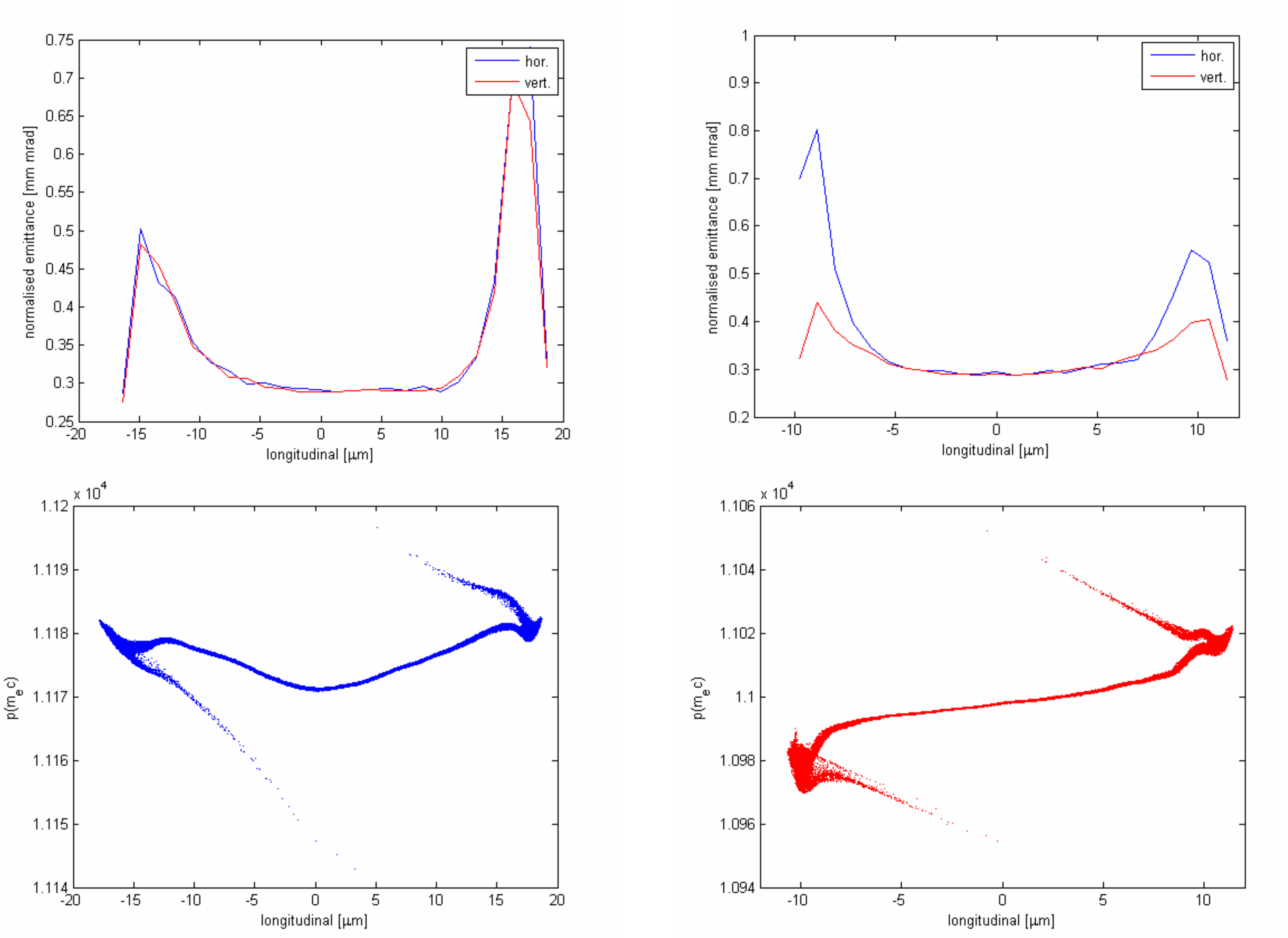
Source	Parameter	Arrival Time	Energy Jitter
Units		fs	%
Tolerance		45	-0.047
Laser time	fs	55.324	-
Gun phase	deg	-	-
Gun gradient	rel	-	-2.585e-04
SB01 Phase	degree	-	4.3150
SB01 Volt	rel	-	-0.0011
SB02 Phase	degree	-	4.2293
SB02 Volt	rel	-	-9.2060e-04
Bunch charge	rel	-	-

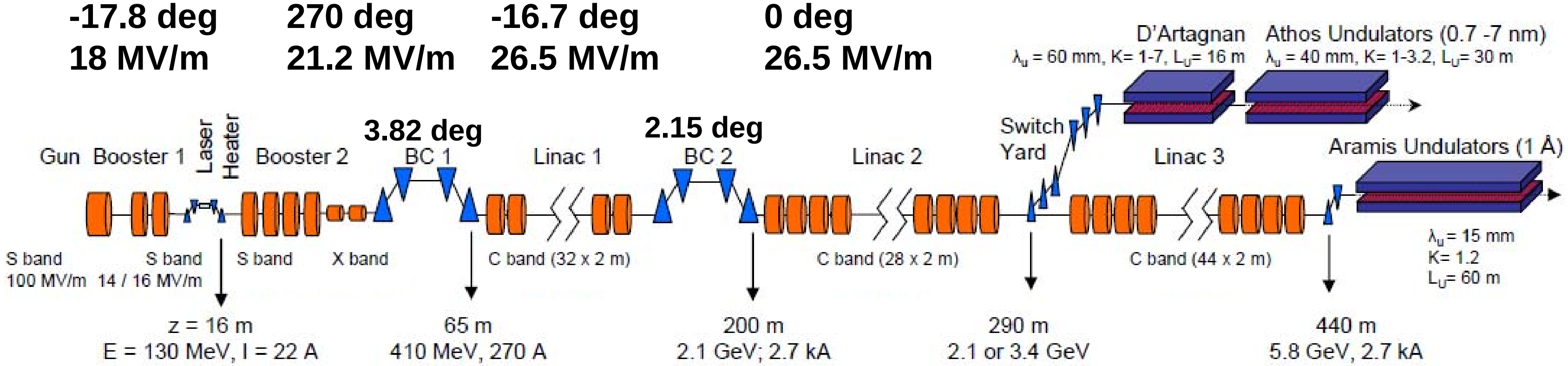

hor.
vert.
normalised emittance [mm mrad]
longitudinal [µm]
x 10^4
p(m_e c)

10pC Layout

- 10pC low charge mode gives the possibility for short pulse beams of high brightness due to low potential emittances.

- Modified layout based on the CDR 200pC case.
- In this layout a small chicane upstream of Aramis is used instead of a dogleg as energy collimator.

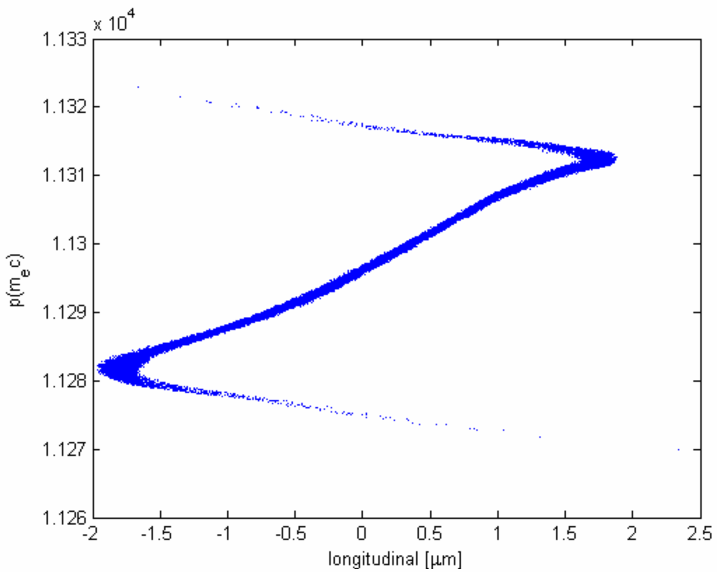
Booster 2:	X-Band:	Linac 1:	Linac 2/3:
-17.8 deg 18 MV/m	270 deg 21.2 MV/m	-16.7 deg 26.5 MV/m	0 deg 26.5 MV/m

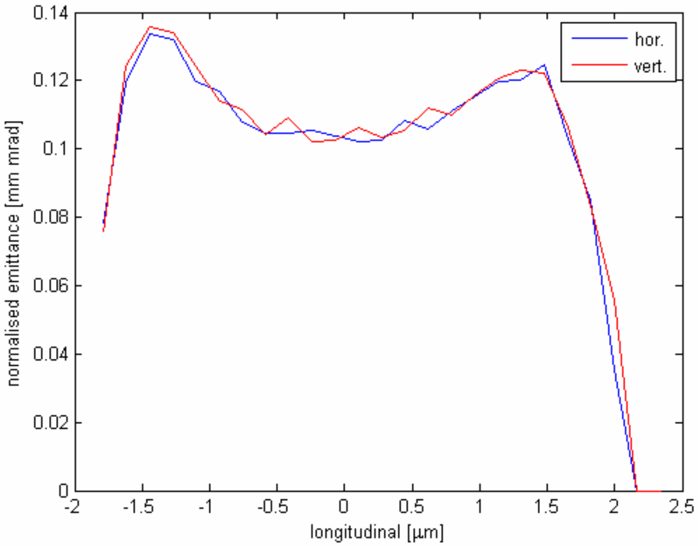


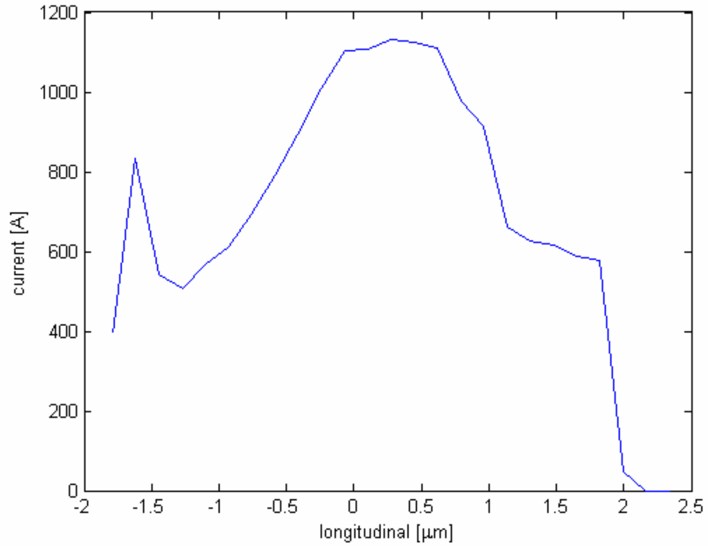
10 pC Operation Mode

- Peak current: 1.1kA
- Slice Emittance: 0.11mm mrad

- Tolerances for this case are studied similar to the 200pC case.

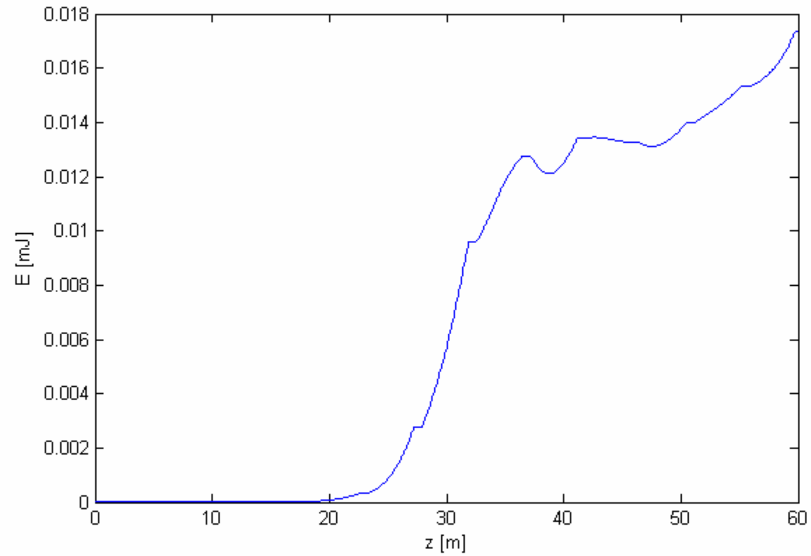


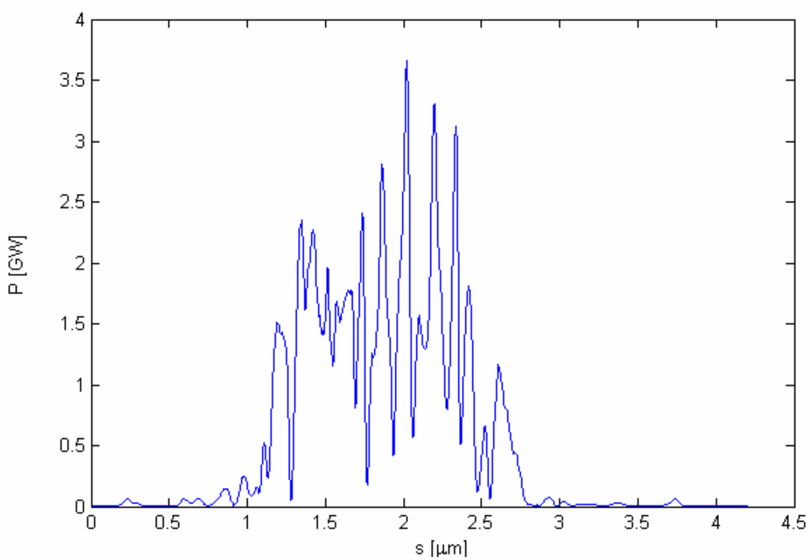


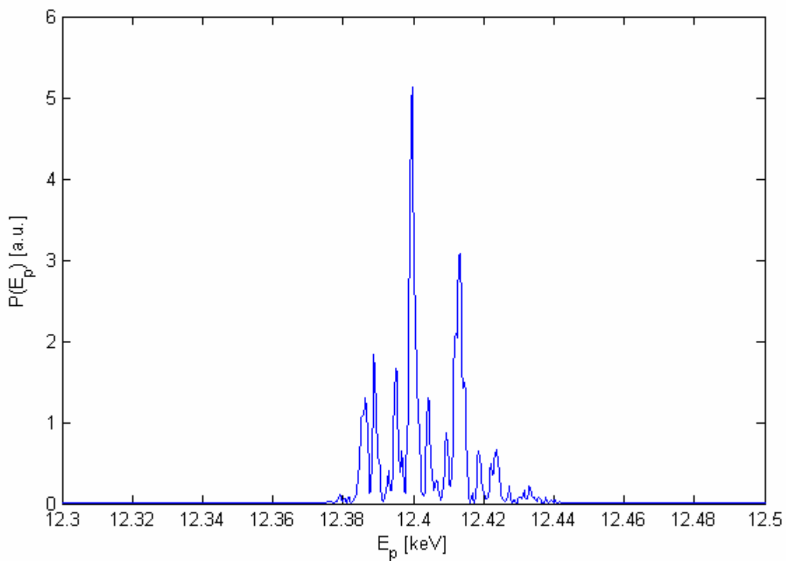


10pC SASE Performance

	200pC	10pC
Saturation	32 m	31 m
E_{sat}	0.11 mJ	7.8μJ
σ_p	20 fs	1.5 fs
<P_{sat}>	2.1GW	2 GW
BW	0.065 %	0.095 %



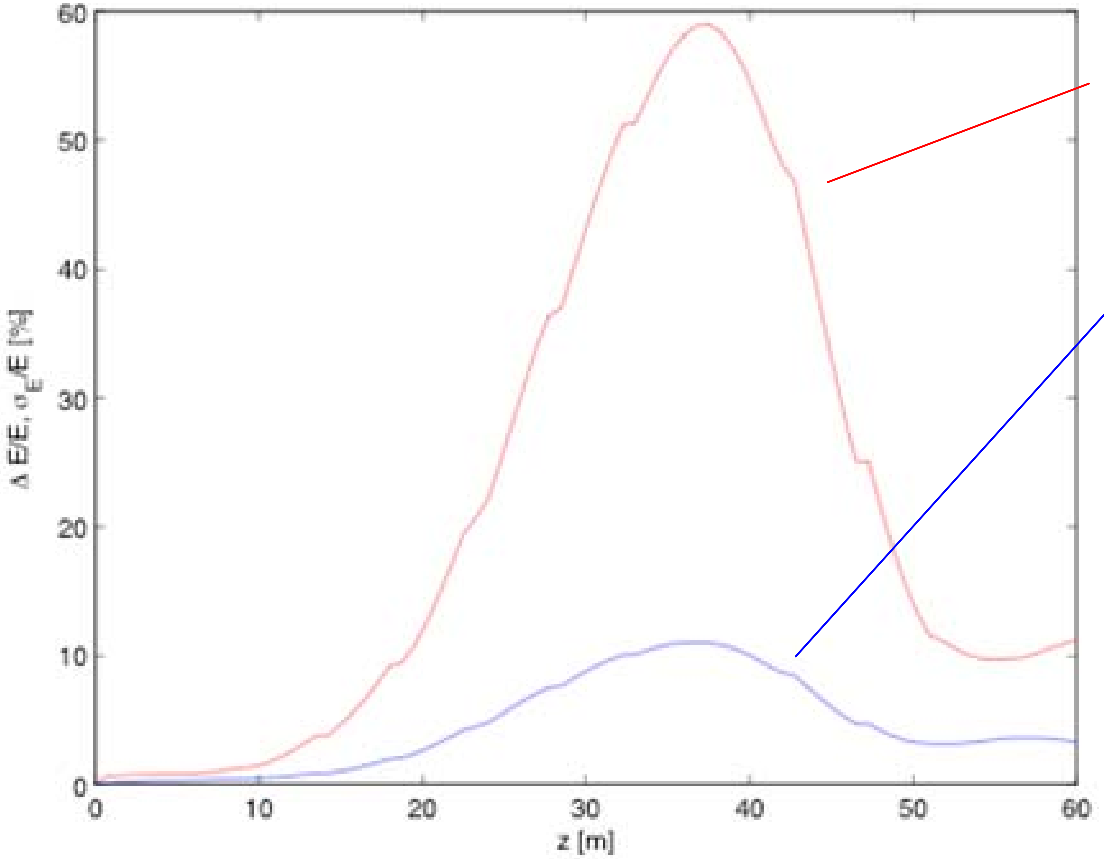




Photon Energy Jitter

Simulation:

50 SASE runs for two different beam current and bunch length.



Difference in mean FEL energy for a 10% change in beam current.

RMS fluctuation in FEL pulse energy with stable beam parameters

Deep Saturation:
Energy proportional to peak current.

Error Sources

- Field strength of bending magnets in 1st bunch compressor
- Arrival time of electron bunch at laser heater
- Mean energy of electron bunch at laser heater
- Amplitude and phase of S-band cavities (4 uncorrelated sources)
- Amplitude and phase of X-band cavity
- Amplitude and phase of C-band cavities of Linac 1 (8 uncorrelated sources)
- Amplitude and phase of C-band cavities of Linac 2 and 3 (18 uncorrelated sources)

Note that all sources of an error are changed the same way. Random errors reduces the sensitivity (and thus relax the tolerance) by the square root of the number of sources.

Sensitivities CDR 200pC

	arrival time [fs]	peak current [%]	energy [%]
S-Band Phase [deg]	-6.4481e+002	-4.5184e+002	+2.4767e-001
S-Band Voltage [rel]	-9.9217e+004	+5.6896e+003	+2.6326e+000
X-Band Phase [deg]	+4.4013e+000	+1.5110e+002	-7.2104e-002
X-Band Voltage [rel]	+9.4602e+003	-1.3639e+002	-5.3702e-001
Linac 1 Phase [deg]	-1.6498e+002	-4.4862e+001	+1.5003e-001
Linac 1 Voltage [rel]	-5.4733e+004	-1.7283e+003	+4.3449e+001
Linac 2 Phase [deg]	-5.9896e-001	-1.1156e-001	-4.6134e-002
Linac 2 Voltage [rel]	+3.3669e+002	+8.8316e+001	+2.5150e+001
Linac 3 Phase [deg]	-9.6394e-001	-1.0173e-001	-7.2491e-002
Linac 3 Voltage [rel]	+5.4210e+002	+9.0954e+001	+3.9517e+001
Charge [pC]	+1.2423e+000	-2.9679e+000	-3.3104e-004
initial arrival time [fs]	-3.6639e-002	+1.2279e-001	+3.1506e-006
Initial Energy [rel]	-4.2527e+004	-1.3546e+003	+2.8118e+000
BC1 angle [rel]	+6.8607e+002	+1.4145e+004	-6.6921e+000
BC2 angle [rel]	-8.3289e+000	+1.8532e+003	-8.4874e-001

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Sensitivities Optimised Layout

+ SwissFEL

	arrival time [fs]	peak current [%]	energy [%]
S-Band Phase [deg]	-2.1111e+002	-4.3983e+001	-3.1529e-001
S-Band Voltage [rel]	-3.9438e+004	+3.8536e+004	-9.3306e+001
X-Band Phase [deg]	+6.7700e-001	+8.1840e+001	-5.7866e-002
X-Band Voltage [rel]	+3.9341e+003	-3.0273e+003	+8.5968e+000
Linac 1 Phase [deg]	-3.7293e+002	-1.6811e+002	+3.2956e-001
Linac 1 Voltage [rel]	-5.6043e+004	-3.4181e+003	+3.0525e+001
Linac 2 Phase [deg]	+1.0093e-002	+8.3872e-002	+5.9109e-005
Linac 2 Voltage [rel]	+3.4473e+002	-1.5199e+001	+2.5930e+001
Linac 3 Phase [deg]	+1.4350e-002	+9.3295e-002	+5.6293e-005
Linac 3 Voltage [rel]	+5.4931e+002	-8.5860e+001	+4.0729e+001
Charge [pC]	+1.0428e+000	-2.6948e+000	+1.0532e-003
initial arrival time [fs]	-3.2489e-002	+7.3075e-002	+1.7125e-005
Initial Energy [rel]	-2.0687e+004	+1.6019e+004	-4.5211e+001
BC1 angle [rel]	+3.8718e+002	+4.7010e+003	-3.5451e+000
BC2 angle [rel]	-1.0756e+002	+4.4288e+003	-3.2400e+000