Bunch Compression Operation at the European XFEL

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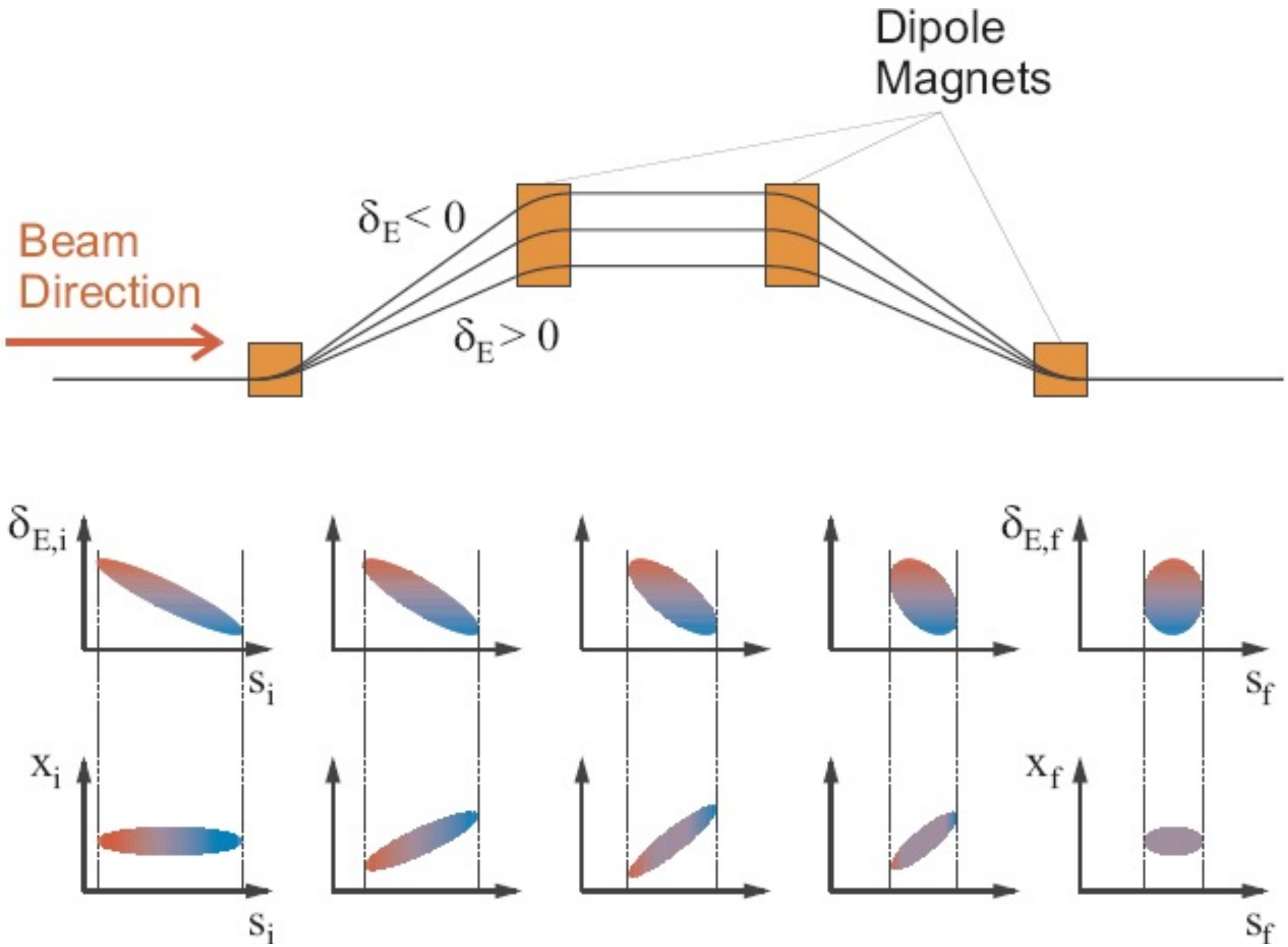
Operator Training
June 2021

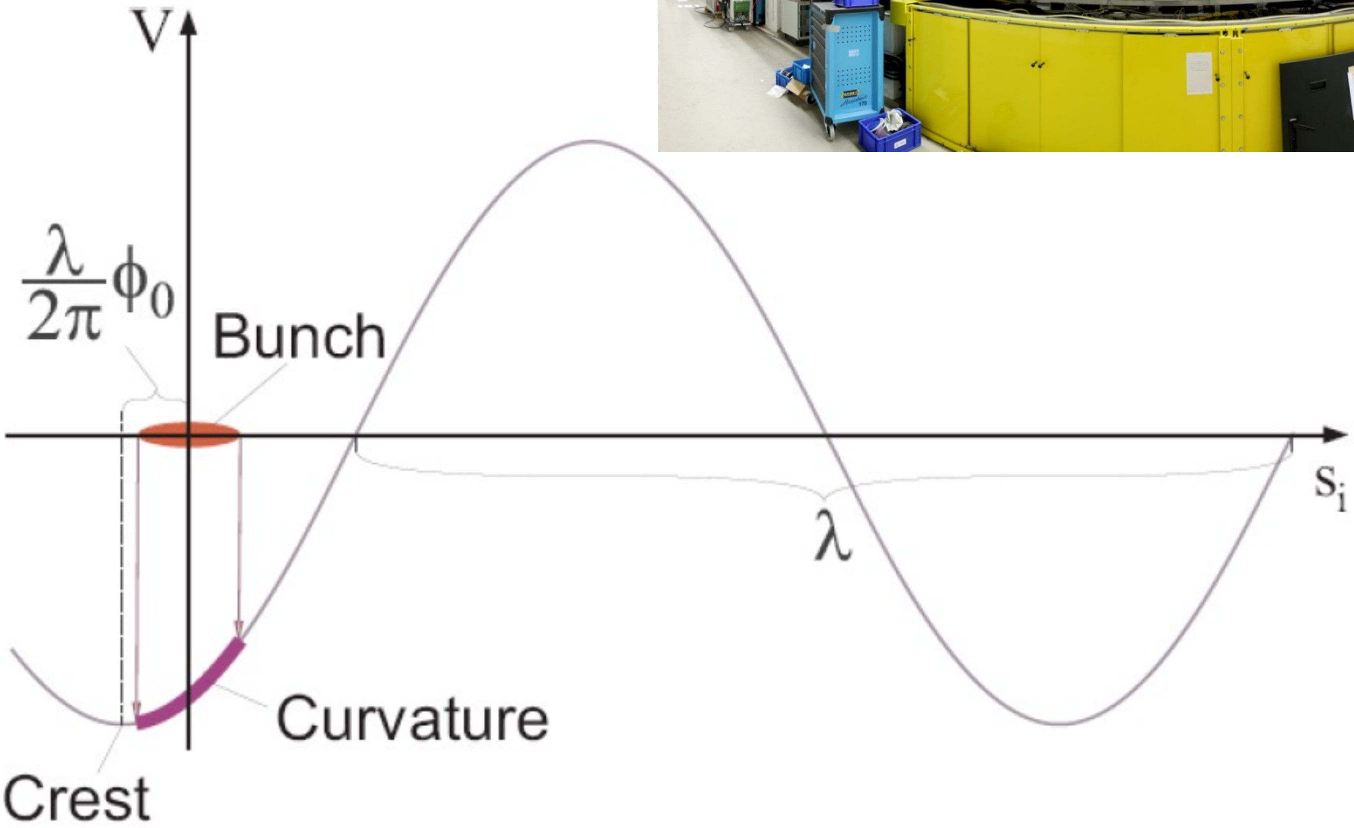
FEL Performance

- FEL performance is determined by the peak current and the emittance – the charge density in 6D.
- Low emittance and high peak current beams are required in the undulators, but not available at feasible electron sources.
- Typically long beams are produced with low emittance and the compressed later.

Basic Principle



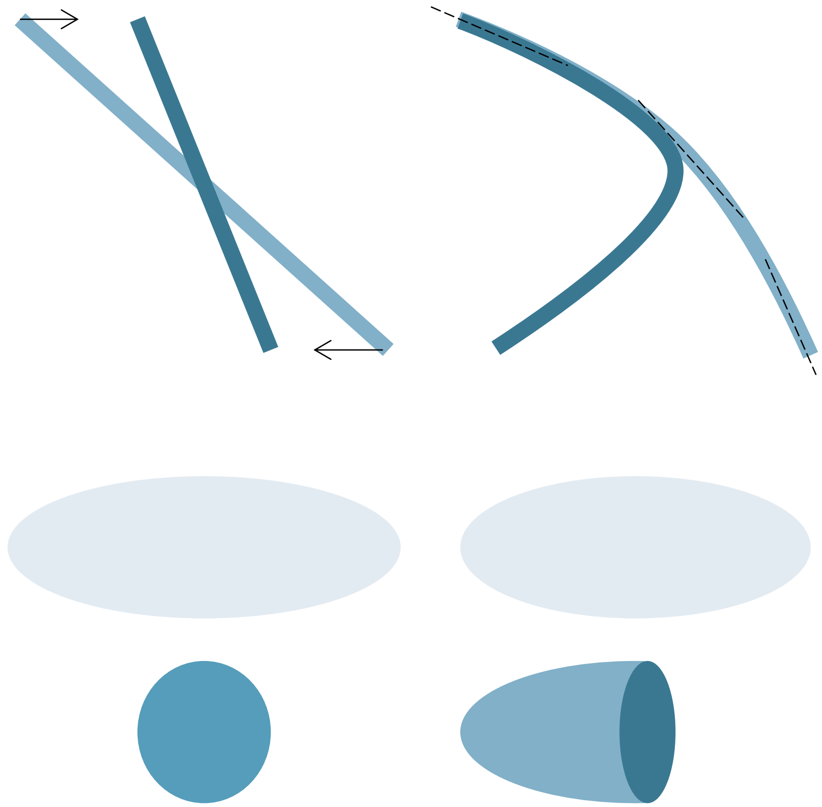
Energy Chirp Generation



“Non-linear” Compression

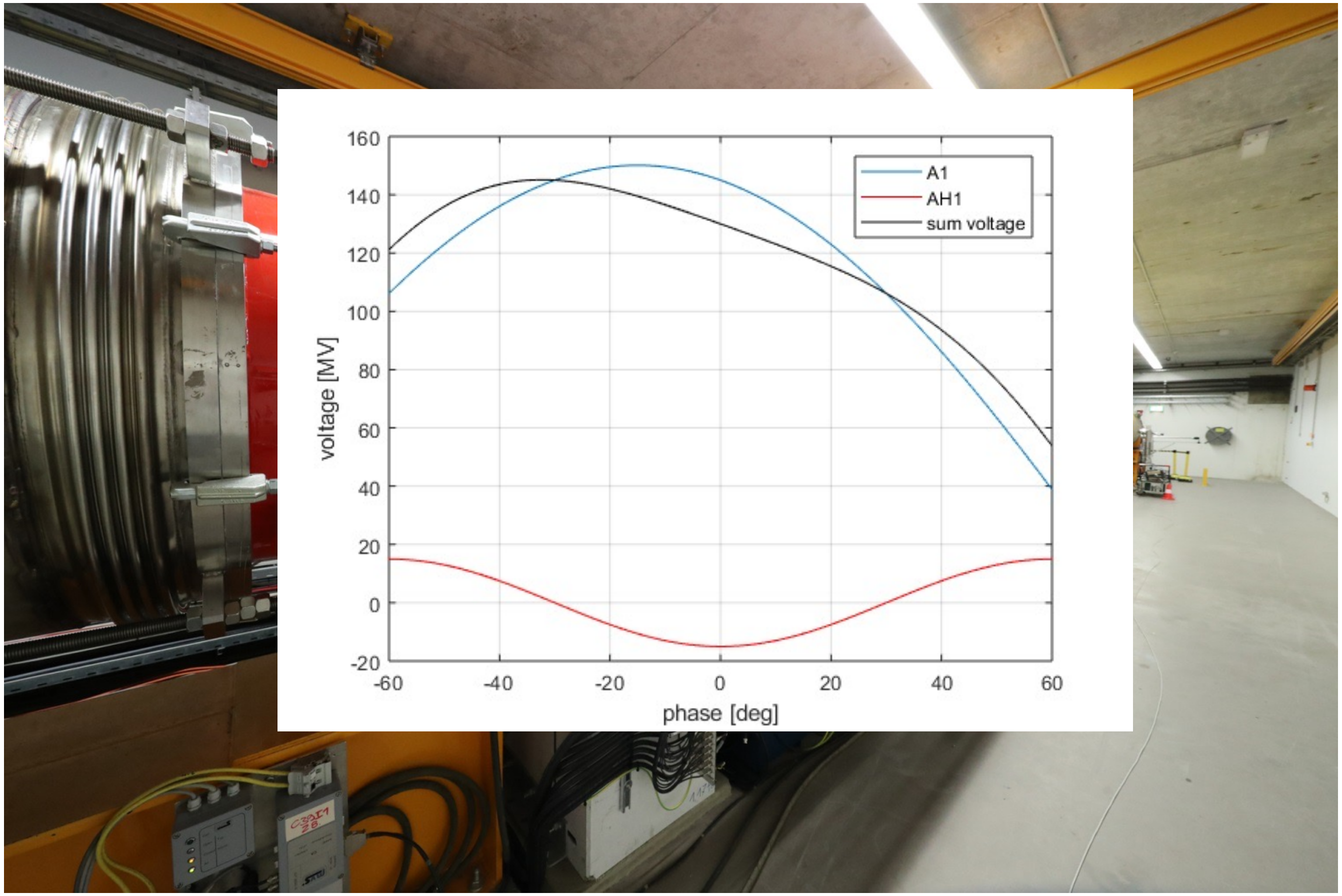
Linear Compression:

Non-Linear Compression:



Phase Space Linearisation

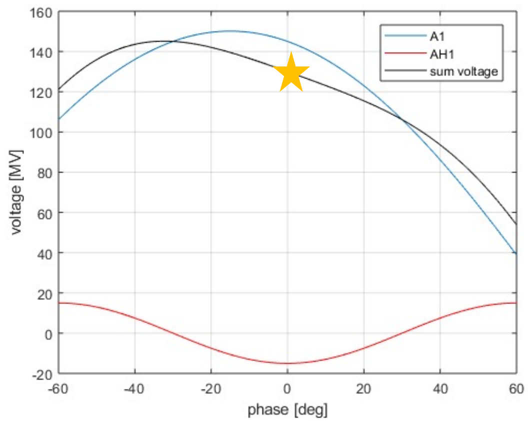
- Higher harmonic RF system is used to remove non-linear chirp
- 3rd harmonic (3.9GHz) at XFEL and FLASH



Sum Voltage

- Setup of RF phase and voltages to get a certain energy chirp is cumbersome

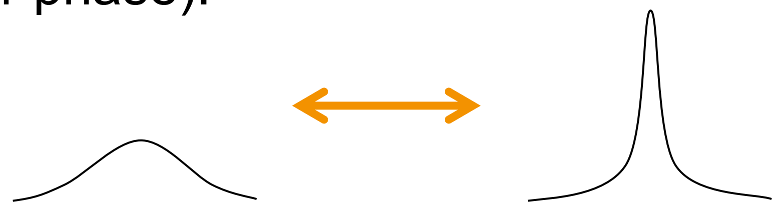
- RF parameters can be directly calculated from the Taylor coefficients (energy, chirp, curvature) at the beam position



- Tuning one of the Taylor coefficients do not change the others, especially the beam energy is not changed (provided that the on-crest phases are correct)

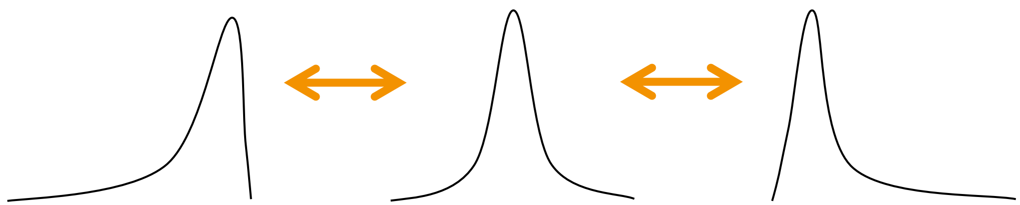
Sum Voltage Effects

- Chirp (mostly A1 phase):

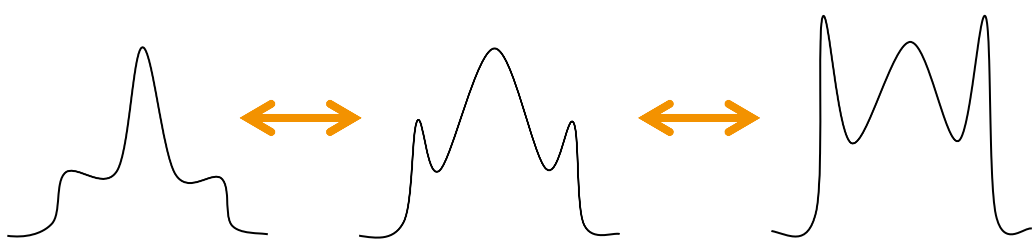


Current profiles

- Curvature (mostly AH1 voltage):



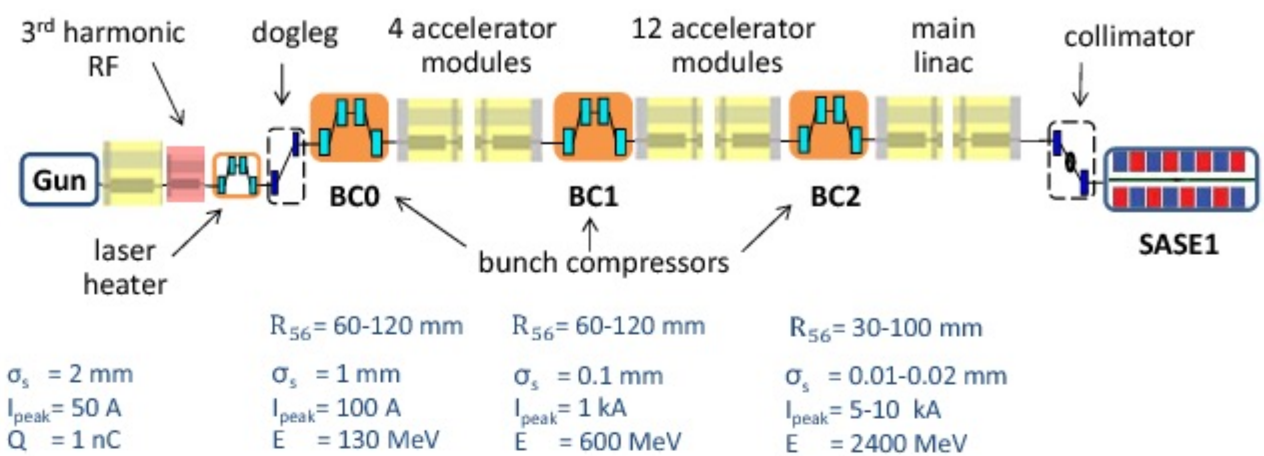
- Third Order “Skewness” (AH1 voltage and phase):



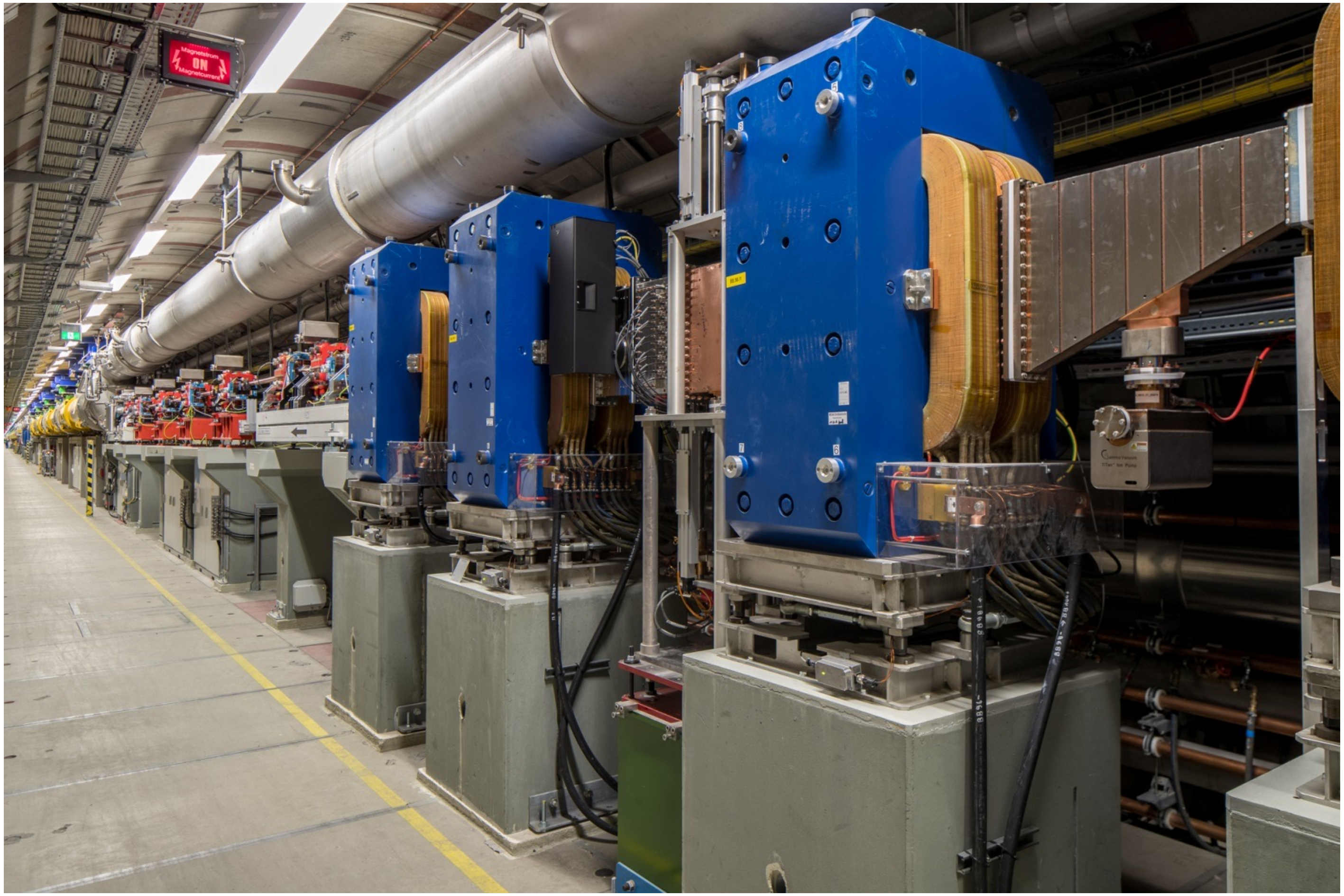
Multi-Stage Compression

- Too much compression at low energies will lead to space-charge dilution of the beam
- Too little compression in the early stage lead to problems with transport of long beams
- Too strong chicanes distort the beam due to synchrotron radiation emission

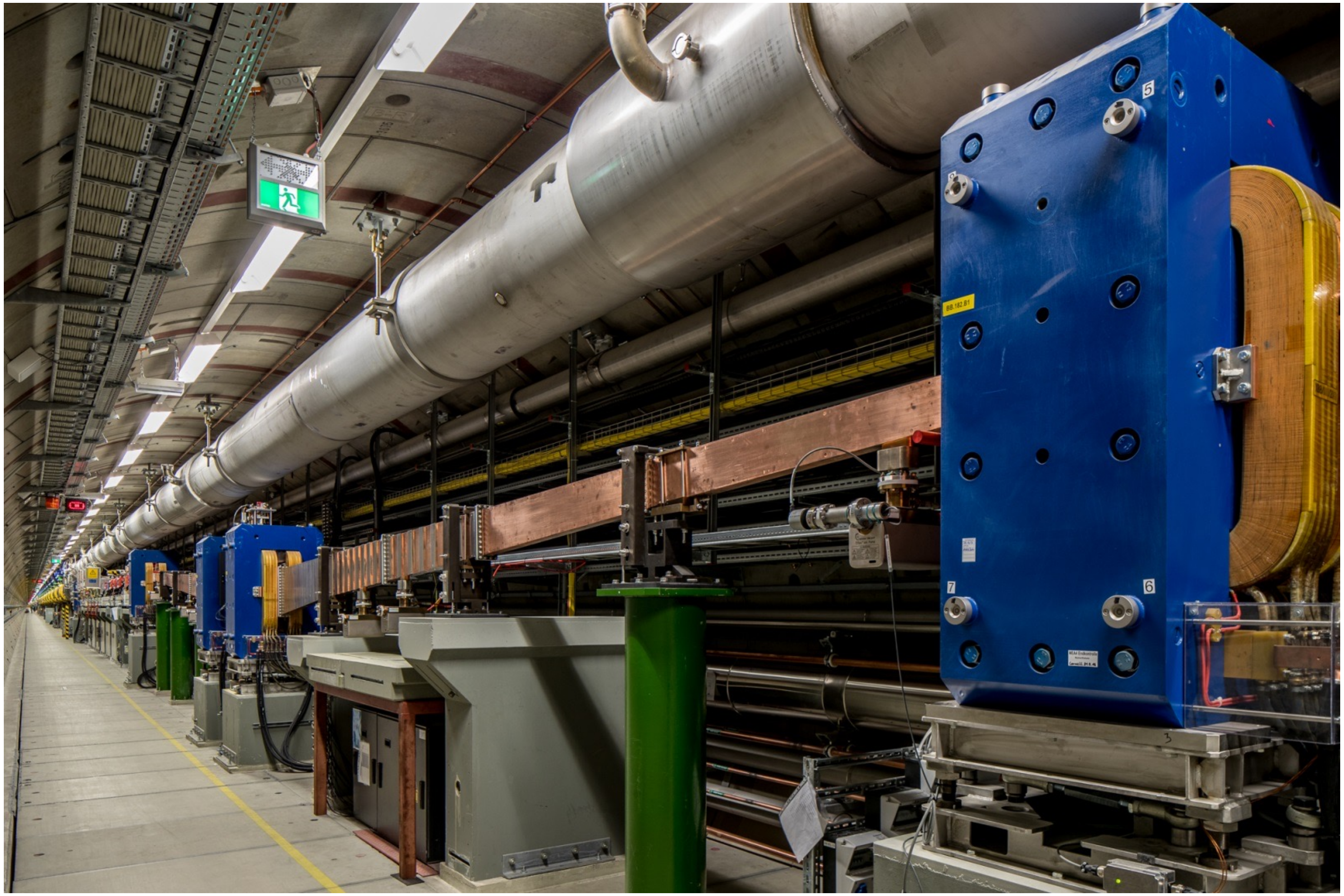
=> Multi-stage compression



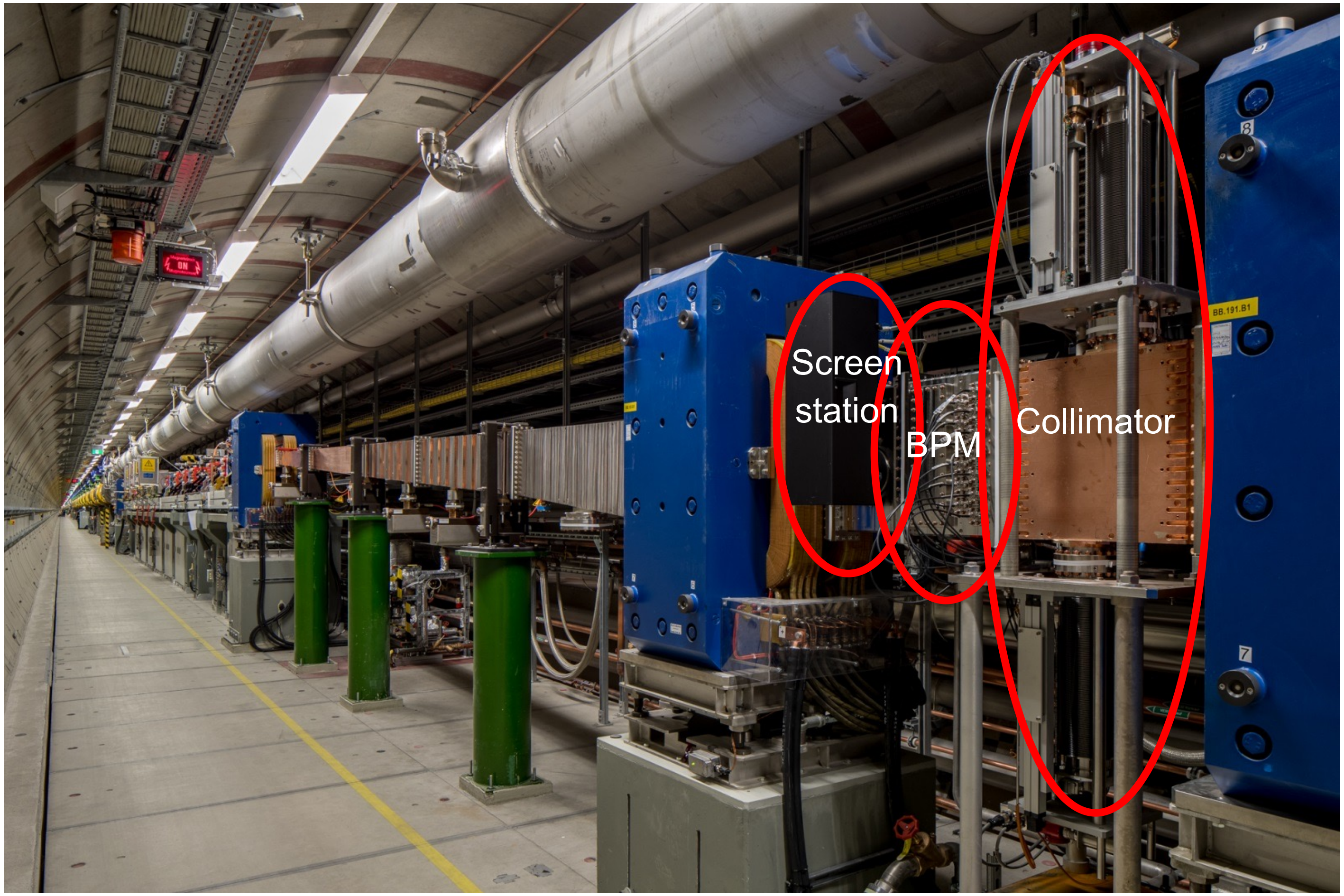
BC0



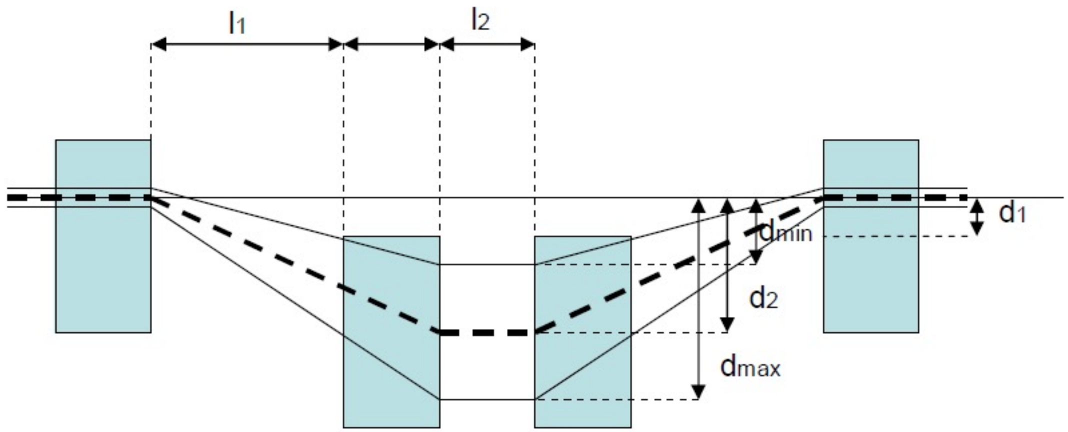
BC1



BC1

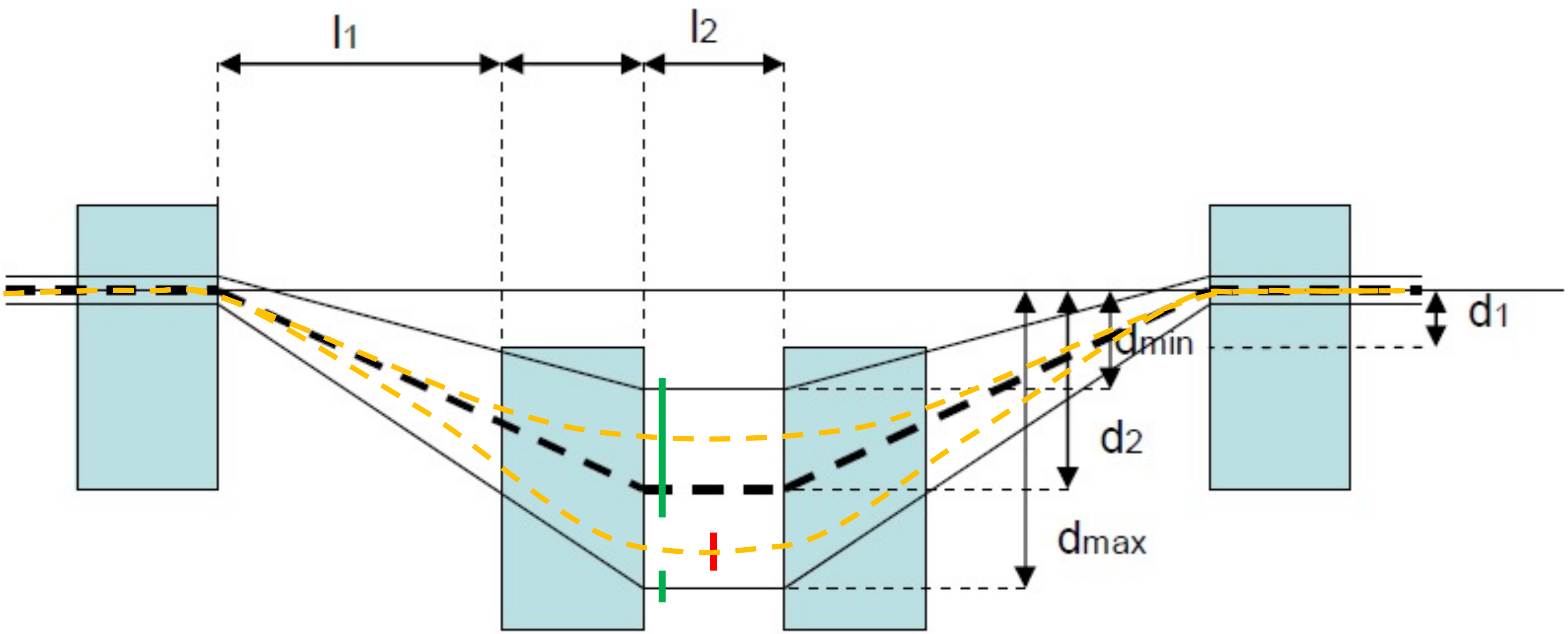


XFEL BC Overview



	R56 range [mm]	Bending Angle [deg]	d_{min} [mm]	d_{max} [mm]	Bend offset d_1 [mm]	Bend offset d_2 [mm]	L_1 [mm]	L_2 [mm]
BC0	0, 30-90	0, 5.67 - 9.82	-20	380	100	200	1	1.5
BC1	20-80	1.93 – 3.86	250	650	100	450	8.5	1.5
BC2	10-60	1.36– 3.34	175	575	100	375	8.5	1.5

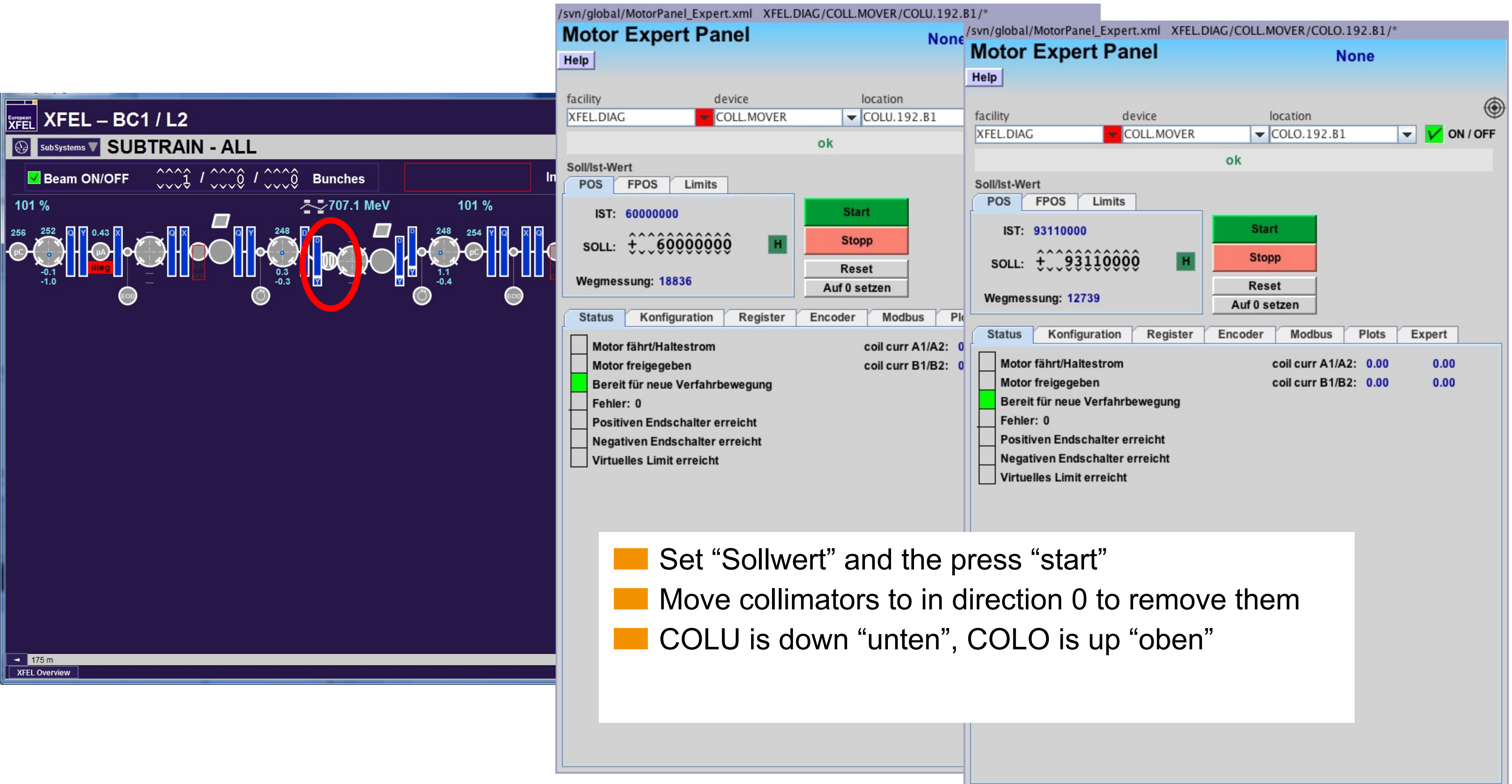
Chamber Overview



Screen
Collimator

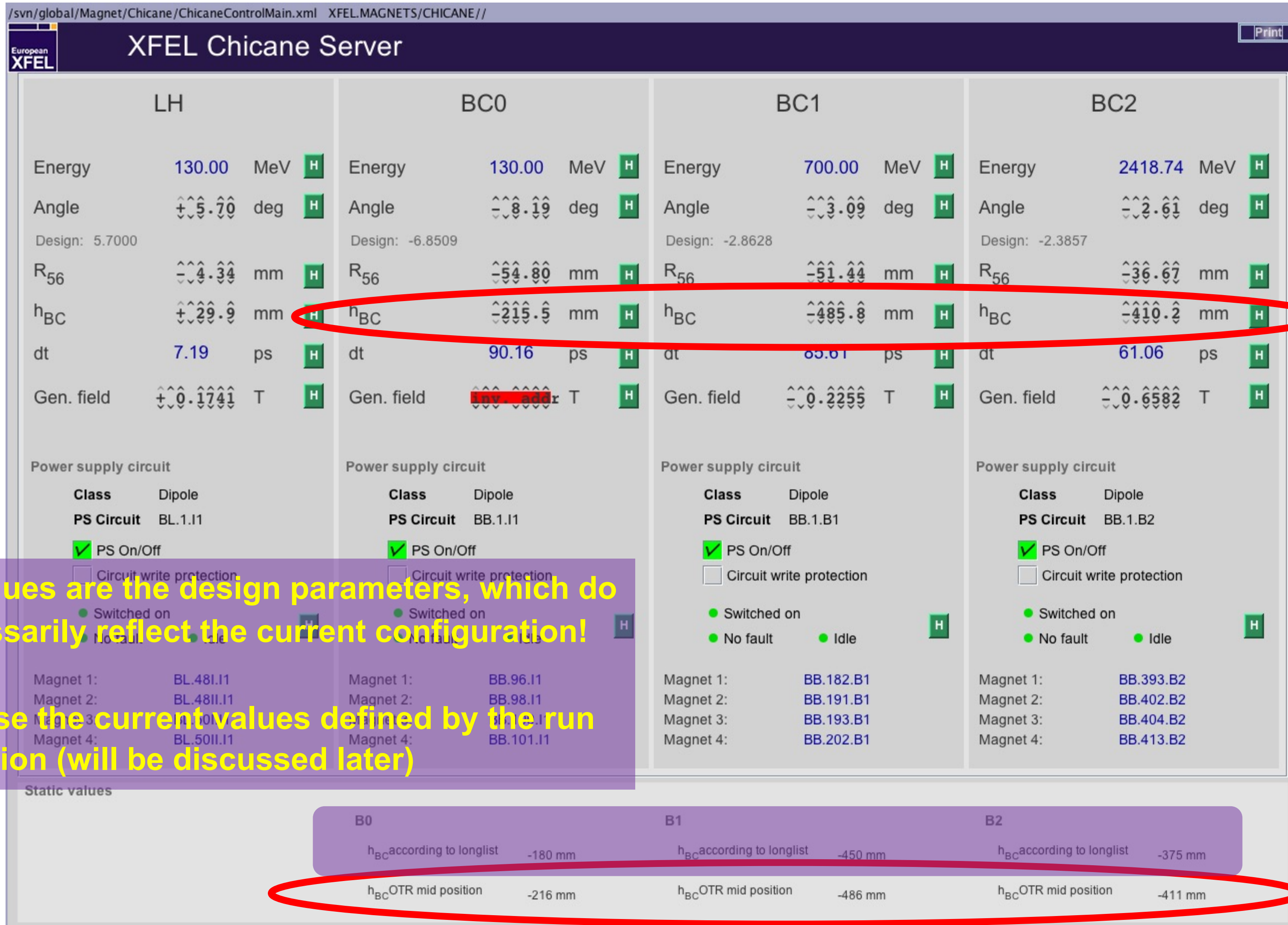
Not to scale!

BC Collimator Control



- Set “Sollwert” and the press “start”
- Move collimators to in direction 0 to remove them
- COLU is down “unten”, COLO is up “oben”

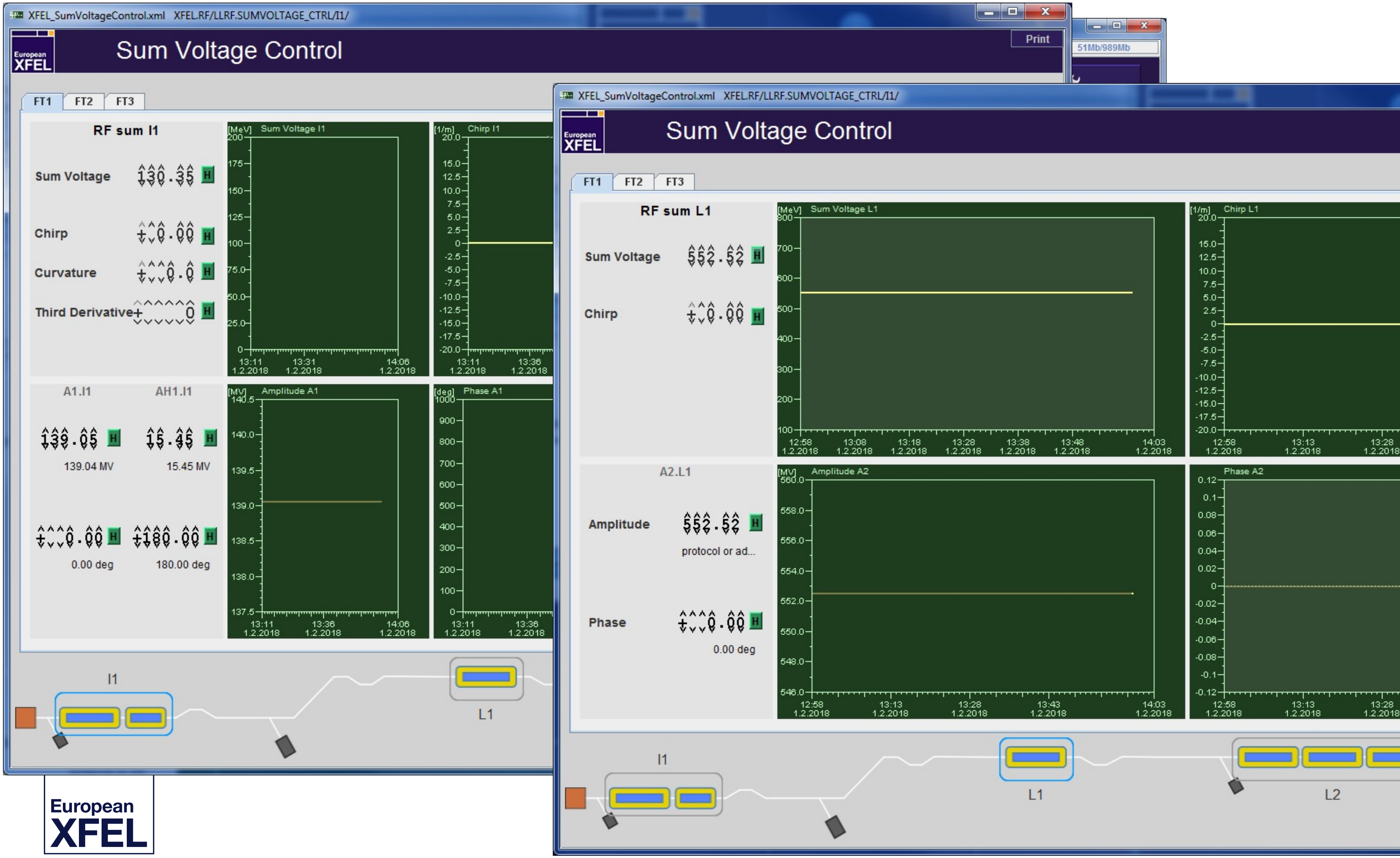
Dipole Setup



These Values are the design parameters, which do not necessarily reflect the current configuration!

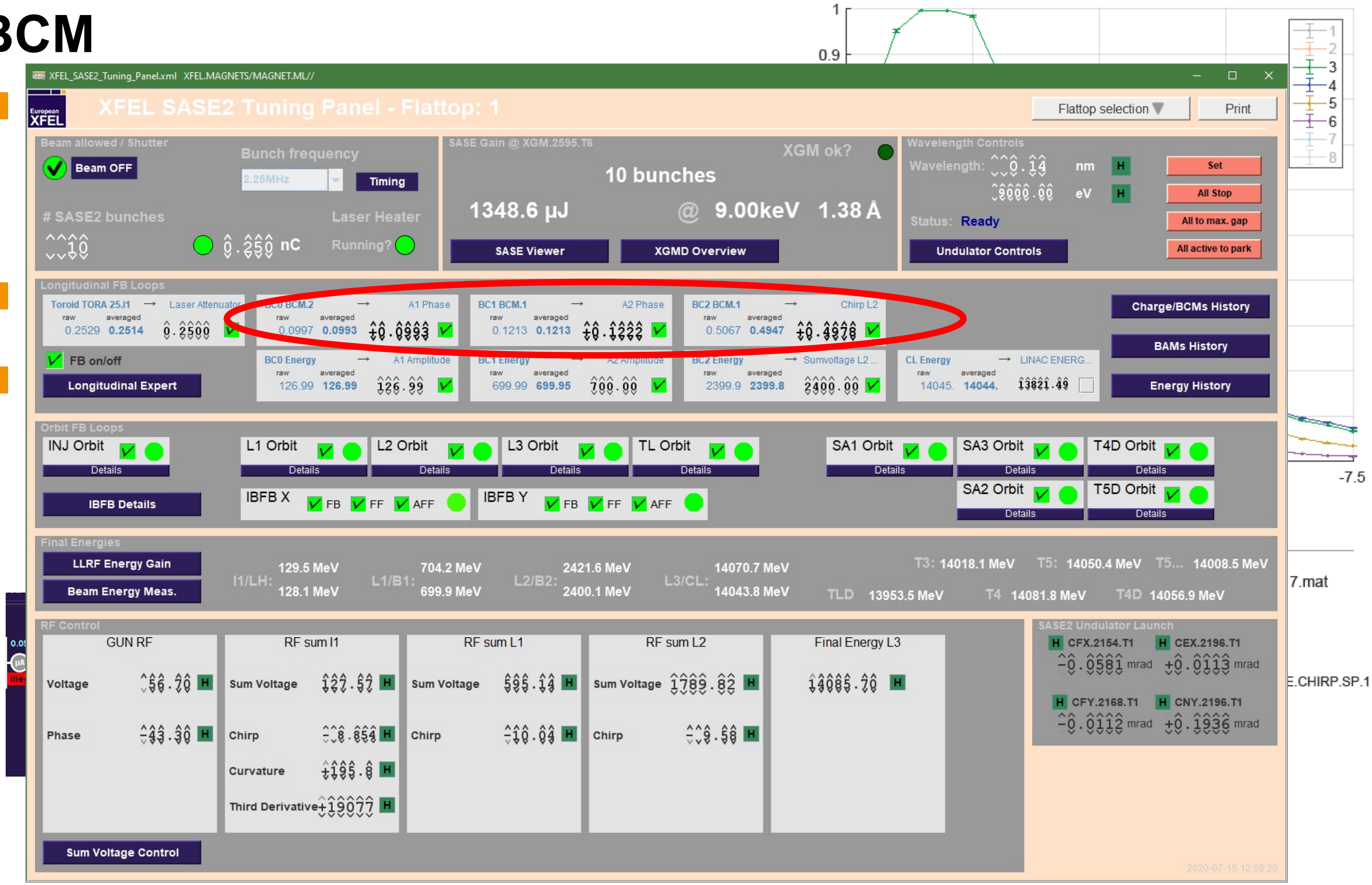
Always use the current values defined by the run coordination (will be discussed later)

RF Setup and Tuning



European XFEL

BCM


XFEL_SASE2_Tuning_Panel.xml XFEL.MAGNETS/MAGNET.ML//
XFEL SASE2 Tuning Panel - Flattop: 1
Flattop selection
Print
Beam allowed / Shutter
Beam OFF
Bunch frequency
2.25MHz
Timing
SASE2 bunches
10
0.250 nC
Laser Heater
Running?
SASE Gain @ XGM.2595.T6
XGM ok?
10 bunches
1348.6 µJ
@ 9.00keV 1.38 Å
SASE Viewer
XGMD Overview
Wavelength Controls
Wavelength: 0.14 nm
9000.00 eV
Status: Ready
Set
All Stop
All to max. gap
All active to park
Undulator Controls
Longitudinal FB Loops
Toroid TORA 25.I1 → Laser Attenuator
raw averaged
0.2529 0.2514 0.2500
BC0 BCM.2 → A1 Phase
0.0997 0.0993 +0.0993
BC1 BCM.1 → A2 Phase
0.1213 0.1213 +0.1222
BC2 BCM.1 → Chirp L2
0.5067 0.4947 +0.4978
FB on/off
Longitudinal Expert
BC0 Energy → A1 Amplitude
126.99 126.99 126.99
BC1 Energy → A2 Amplitude
699.99 699.95 700.00
BC2 Energy → Sumvoltage L2
2399.9 2399.8 2400.00
CL Energy → LINAC ENERG...
14045. 14044. 13821.49
Charge/BCMs History
BAMs History
Energy History
Orbit FB Loops
INJ Orbit
L1 Orbit
L2 Orbit
L3 Orbit
TL Orbit
SA1 Orbit
SA3 Orbit
T4D Orbit
SA2 Orbit
T5D Orbit
Details
IBFB Details
IBFB X FB FF AFF
IBFB Y FB FF AFF
Final Energies
LLRF Energy Gain
Beam Energy Meas.
I1/LH: 129.5 MeV 128.1 MeV
L1/B1: 704.2 MeV 699.9 MeV
L2/B2: 2421.6 MeV 2400.1 MeV
L3/CL: 14070.7 MeV 14043.8 MeV
T3: 14018.1 MeV
T5: 14050.4 MeV
T5... 14008.5 MeV
TLD 13953.5 MeV
T4 14081.8 MeV
T4D 14056.9 MeV
RF Control
GUN RF
Voltage 56.70
Phase -43.30
RF sum I1
Sum Voltage 127.57
Chirp -8.854
Curvature +195.8
Third Derivative +19077
RF sum L1
Sum Voltage 595.14
Chirp -10.04
RF sum L2
Sum Voltage 1789.82
Chirp -9.58
Final Energy L3
14085.70
Sum Voltage Control
SASE2 Undulator Launch
CFX.2154.T1 -0.0581 mrad
CEX.2196.T1 +0.0113 mrad
CFY.2168.T1 -0.0112 mrad
CNY.2196.T1 +0.1936 mrad
2020-07-15 12:58:20
1
0.9
-7.5
7.mat
E.CHIRP.SP.1

Compression Setup Procedure I

Chicane Magnet Setup

- Make sure BC dipoles are set correctly and cycled and the reference energy of the dipoles are correct (130MeV for BC0, 700MeV for BC1, and 2400MeV for BC2)

	BC0 angle [deg]	BC1 angle [deg]	BC2 angle [deg]	BC0 R_{56} [mm]	BC1 R_{56} [mm]	BC2 R_{56} [mm]
250pC	-7.83	-3.05	-2.36	-50	-50	-30
100pC	-7.34	-3.05	-2.36	-43.8	-50	-30

- Set the correct optics for this bending angle is set in the machine

250pC	Inj76/XX Injector (a)symetric FODO 76/XX	BC2 2019
100pC	Inj76/XX Injector (a)symetric FODO 76/XX BC0 = -7.34	BC2 2019

https://confluence.desy.de/display/XFELOp/Bunch+Compression+Setup+Procedure

Compression Setup Procedure II

- RF Setup
  - Deactivate the compression feedbacks
  - phase scan to set on-(anti-)crest to A1,AH1,L1,L2 to 0(180)deg
  - Set the design configuration by using the Sum Voltage Knobs to (**250pC**/**100pC**):

	sum voltage	chirp	curvature	third derivative
I1	130.0	-9.1 / -9.8	270 / 265	25966 / 20000
L1	569.8	-9.1 / -9.4	-	-
L2	1698.7	-12 / -8	-	-

The RC or an expert might suggest new values here. Alternatively parameters from a previous good SASE delivery run might be used.

  - scale the cold magnets between A1 and AH1 to the correct energy

https://confluence.desy.de/display/XFELOp/Bunch+Compression+Setup+Procedure

Compression Setup Procedure III

- confirm that beam energy is set to 130, 700, 2400MeV at I1, B1, and B2
- Check with B1D and B2D or at least with the BPMS energy server if in hurry.
- Correct by using the sum voltage knob in the corresponding linac (L1 or L2).
- The I1T energy server should read 130 which typically corresponds to about 128MeV in the LH.
- When set up the above values subtract up to 150 from the 'curvature' parameter in I1 do this in steps of max 10.
- close compression feedbacks by transferring the **current** compression monitor reading to the target value (arrow button) and then set the activation checkbox.

https://confluence.desy.de/display/XFELOp/Bunch+Compression+Setup+Procedure

SASE Tuning

- open longitudinal feedback loops

- use chirps first L1, I1, and L2 in that order
  - I1 is the most sensitive tune in the 0.1 or 0.01 range
  - L1 should be tuned in with 0.1 steps
  - L2 is the least sensitive knob step sizes of 0.1 to 1 can be used. **Make sure that the L2 phase does not exceed 30deg!**

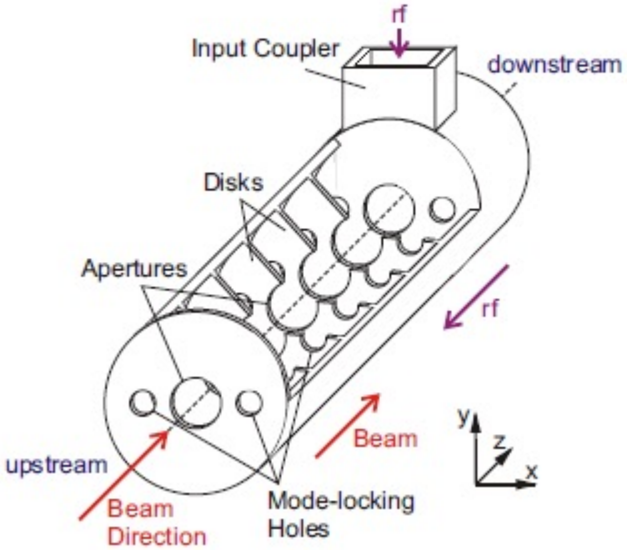
- If chirp tuning is not successful adjust curvature in I1. Steps of 1 or 10.

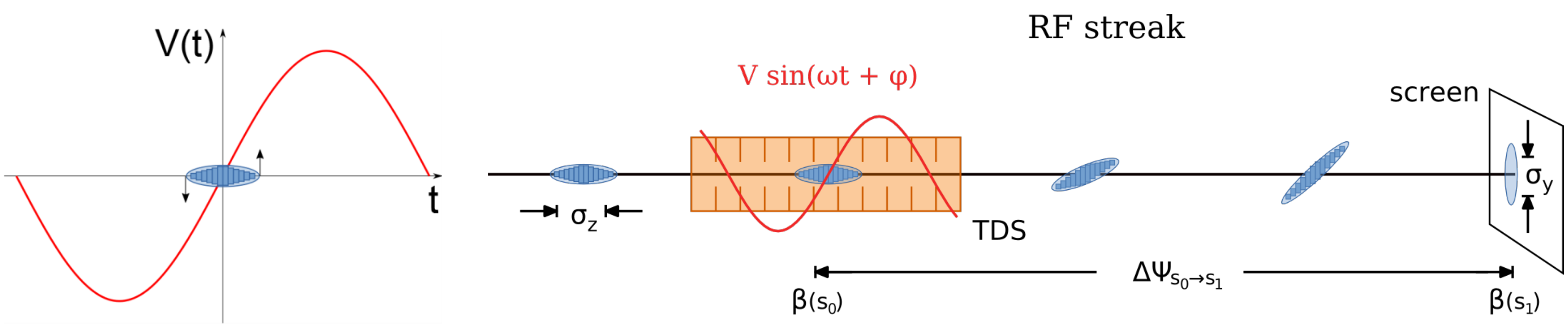
- The I1 third derivative knob can be used in steps of 100 or 1000. Smaller steps have no real impact!

- After tuning is finished e.g. after reaching a new SASE optimum, close the longitudinal feedbacks **after transferring the BCM signals to the target values using the arrow button.**

https://confluence.desy.de/display/XFELOp/Bunch+Compression+Setup+Procedure

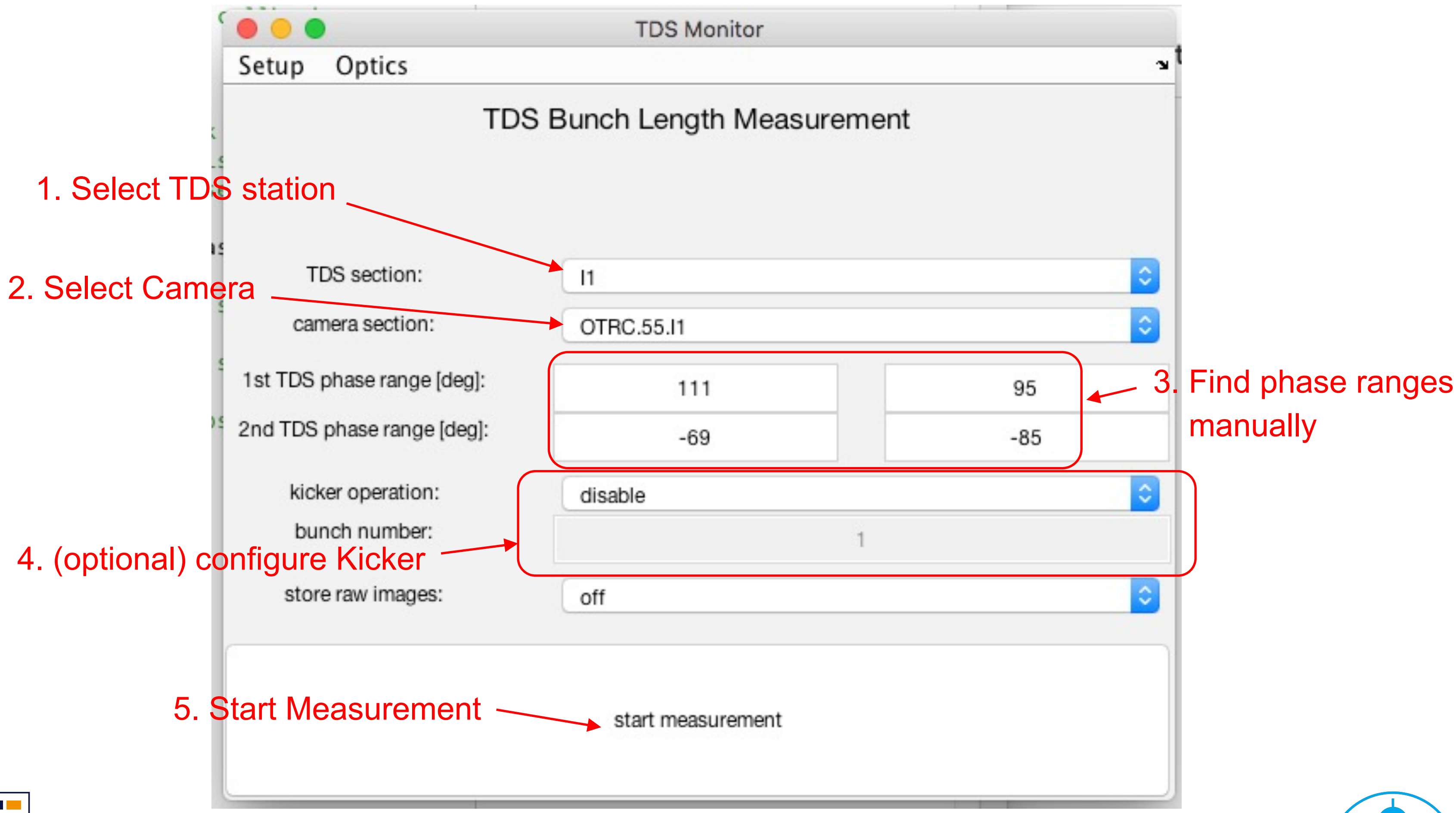
Transverse Deflecting Structure (TDS)





TDS Measurements

- TDS Monitor (Main Taskbar-> Beam Dynamics->TDS Monitor)

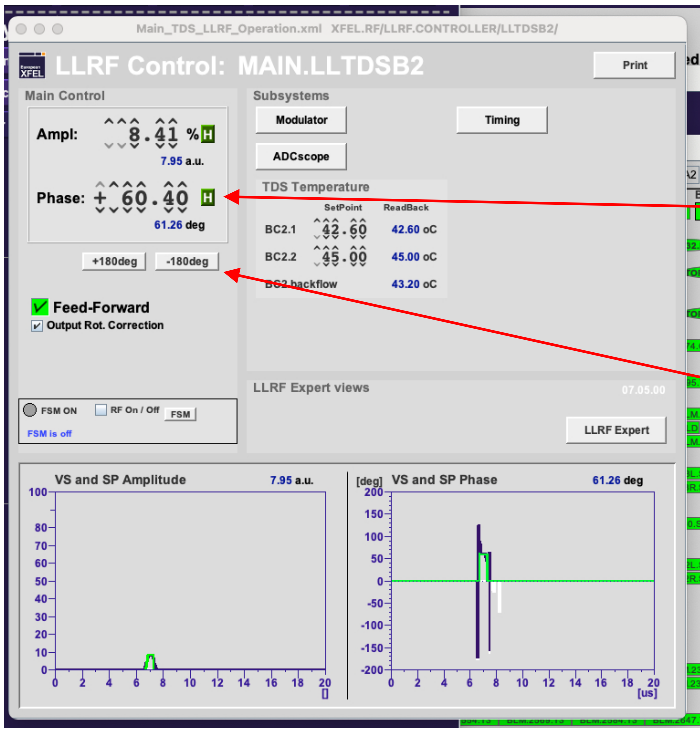


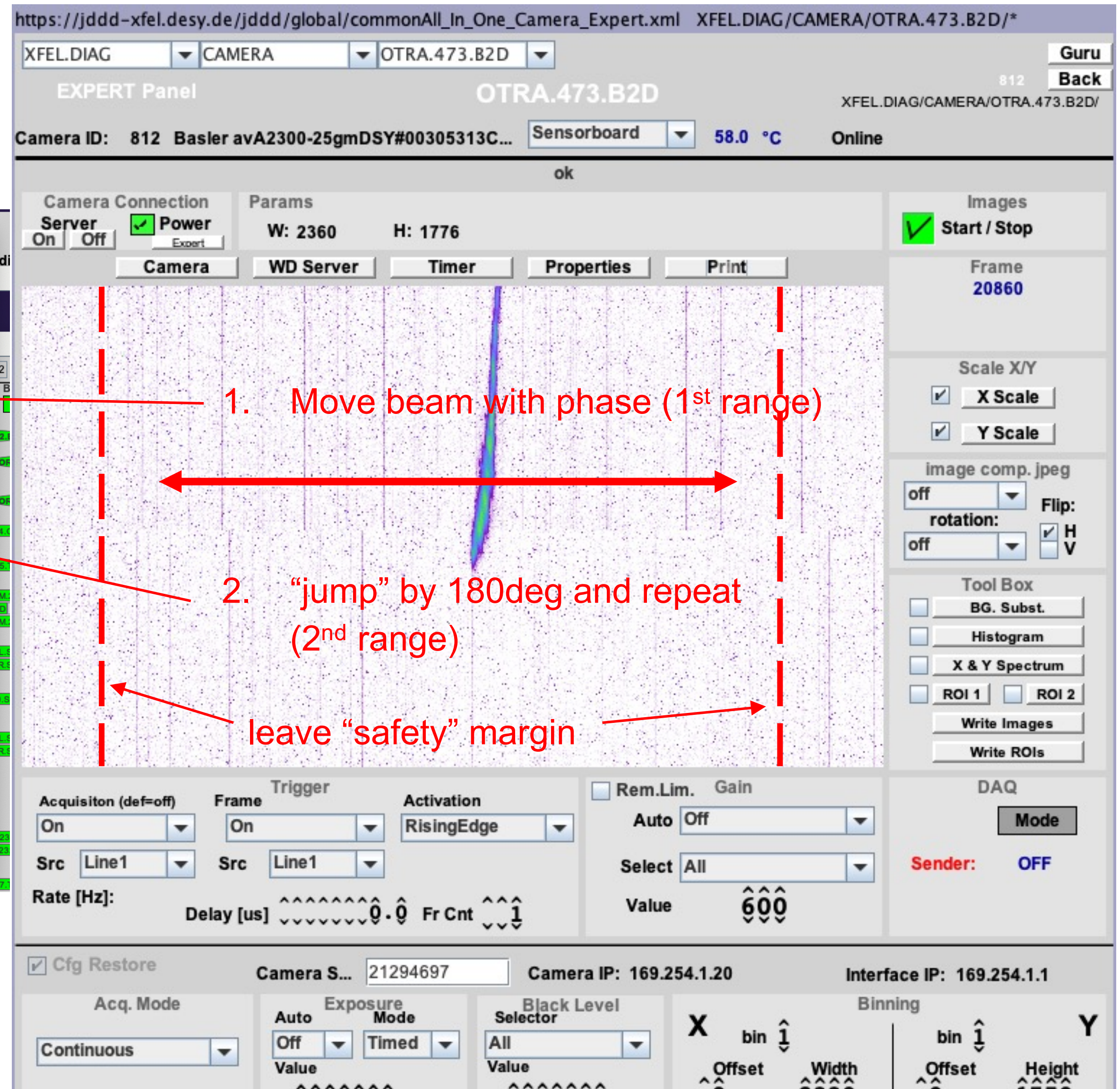
TDS Phase Range Setup

Example:

B2 in spectrometer B2D

in I1 the streak direction is horizontal





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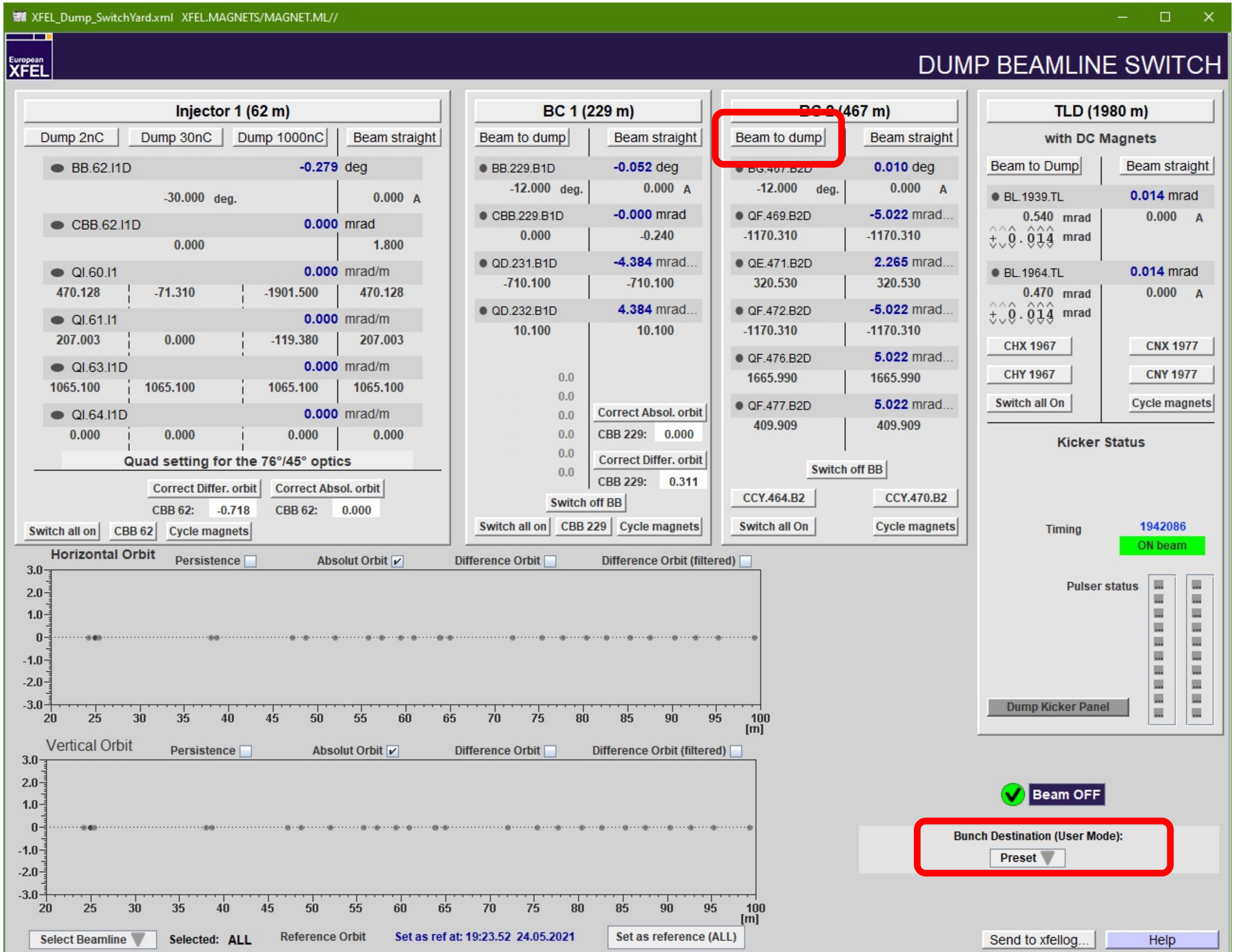
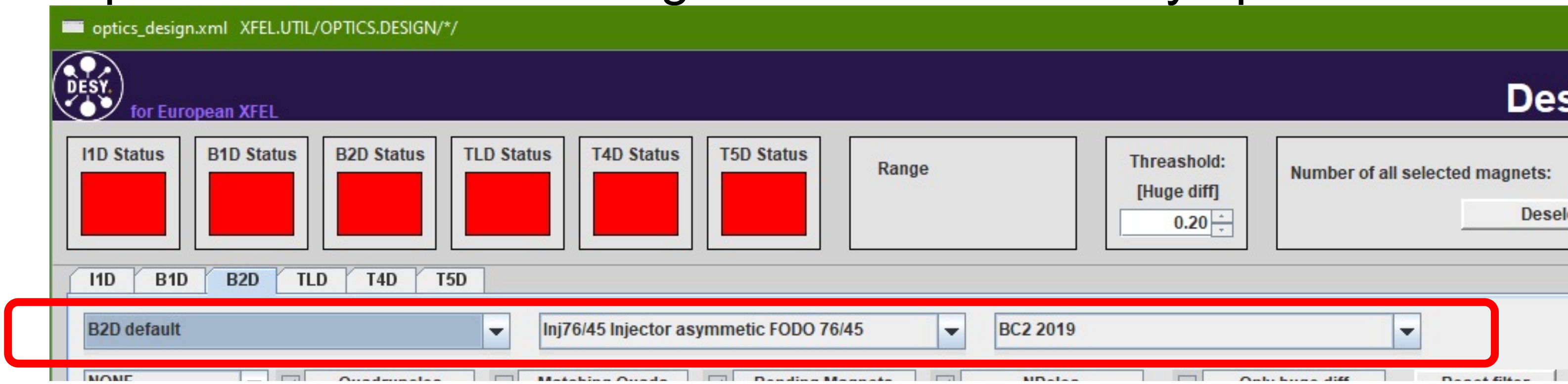
Setup B2D Measurements

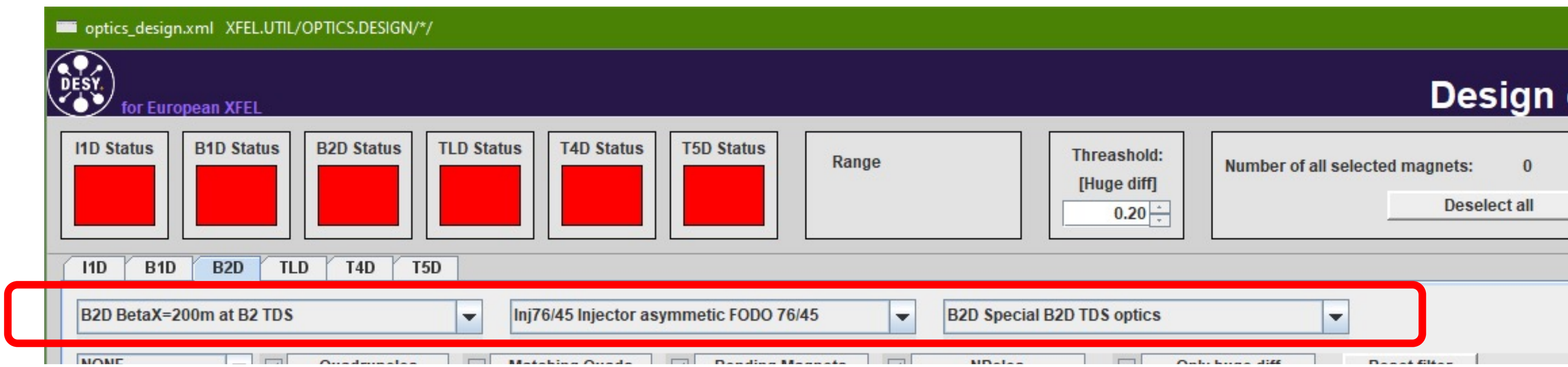


Setup B2D Measurements

- After Dump switch was used change from SASE delivery optics



to High-res TDS optics – beta at TDS is increased to 200m

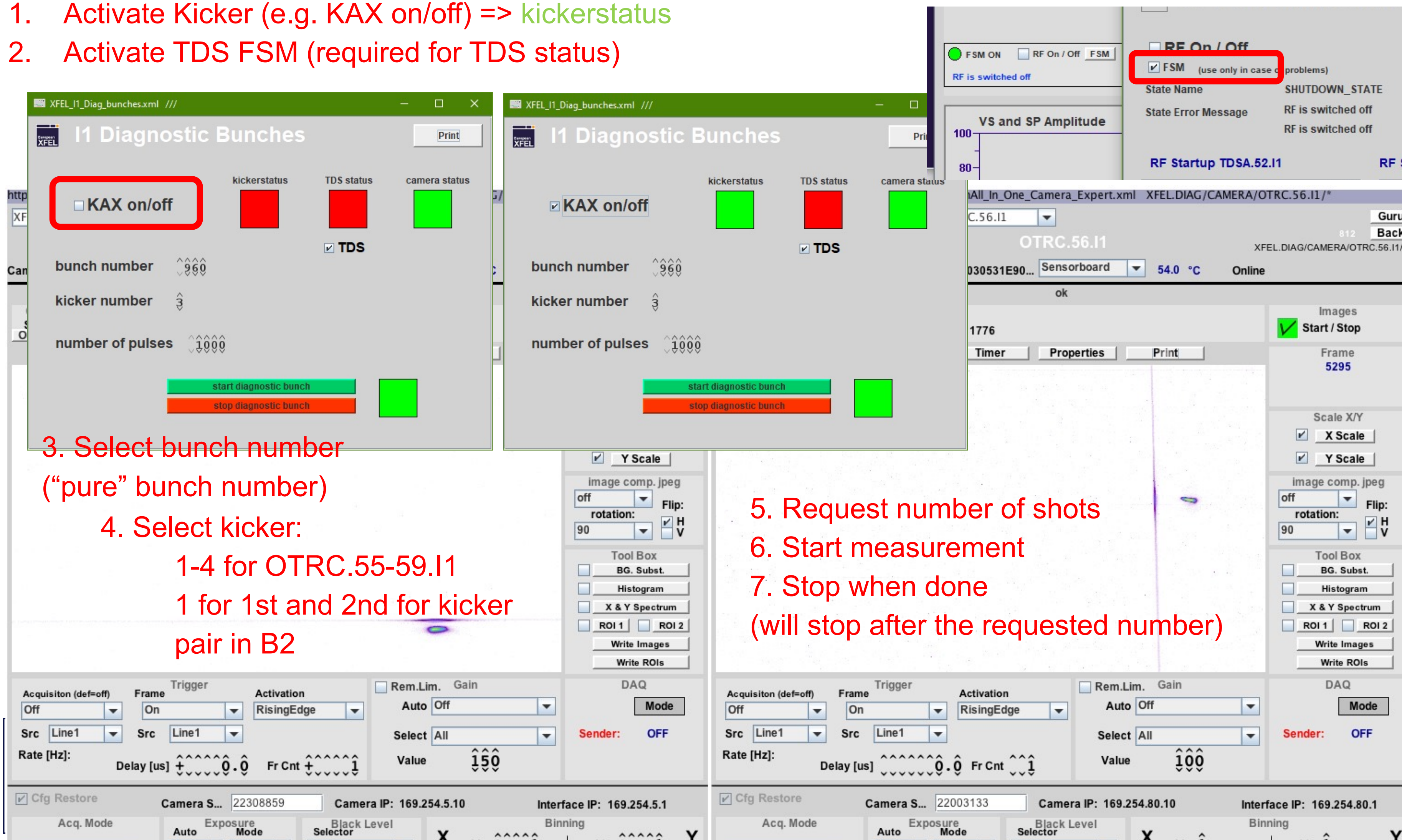


set and cycle to selected design – reset when done with measurements

Off-Axis TDS Operation

- (Main Taskbar-> Beam Dynamics->Diag Bunches Inj/BC2)

1. Activate Kicker (e.g. KAX on/off) => kickerstatus
2. Activate TDS FSM (required for TDS status)



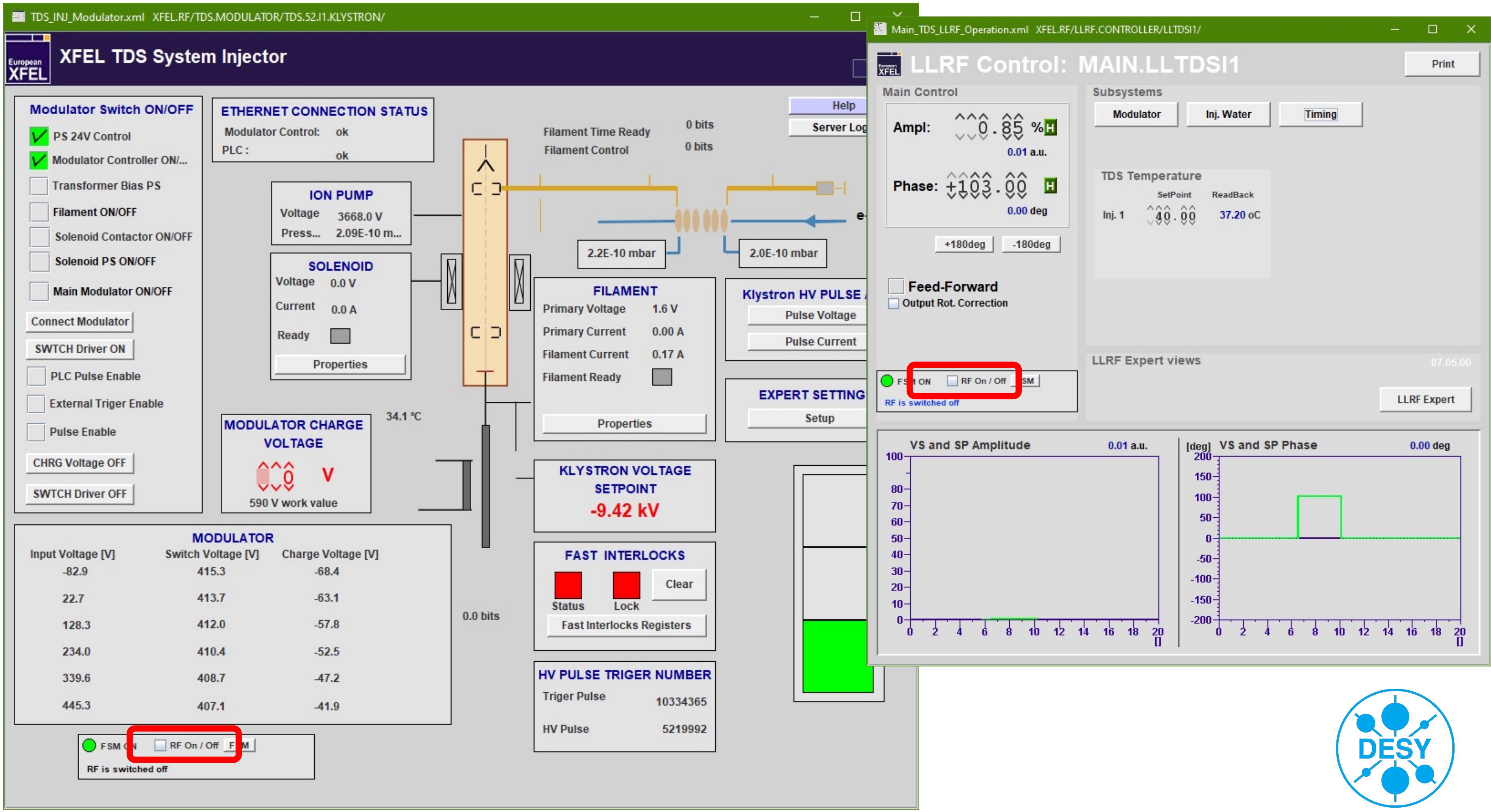
3. Select bunch number
("pure" bunch number)

4. Select kicker:
   1-4 for OTRC.55-59.I1
   1 for 1st and 2nd for kicker pair in B2

5. Request number of shots
6. Start measurement
7. Stop when done
(will stop after the requested number)

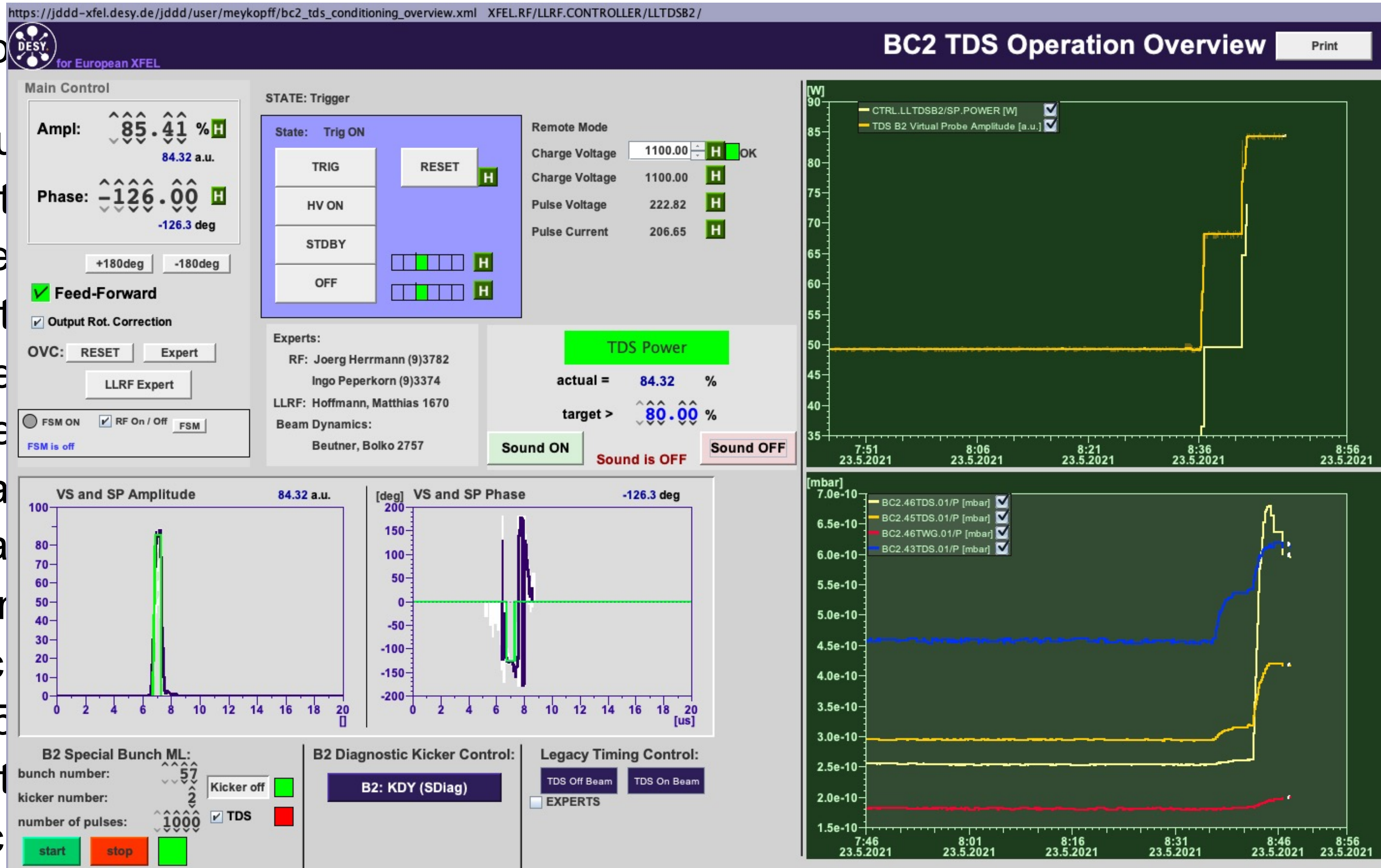
TDS Operation I1

- RF system is switched on using the “FSM RF On/Off”-button



TDS Operation B2

- Keep
- Manu
  - Set
    “Fe
  - Set
  - Pre
  - Pre
  - Wa
    rea
    fror
  - Inc
    115
  - Set
  - Inc
    while monitoring vacuum



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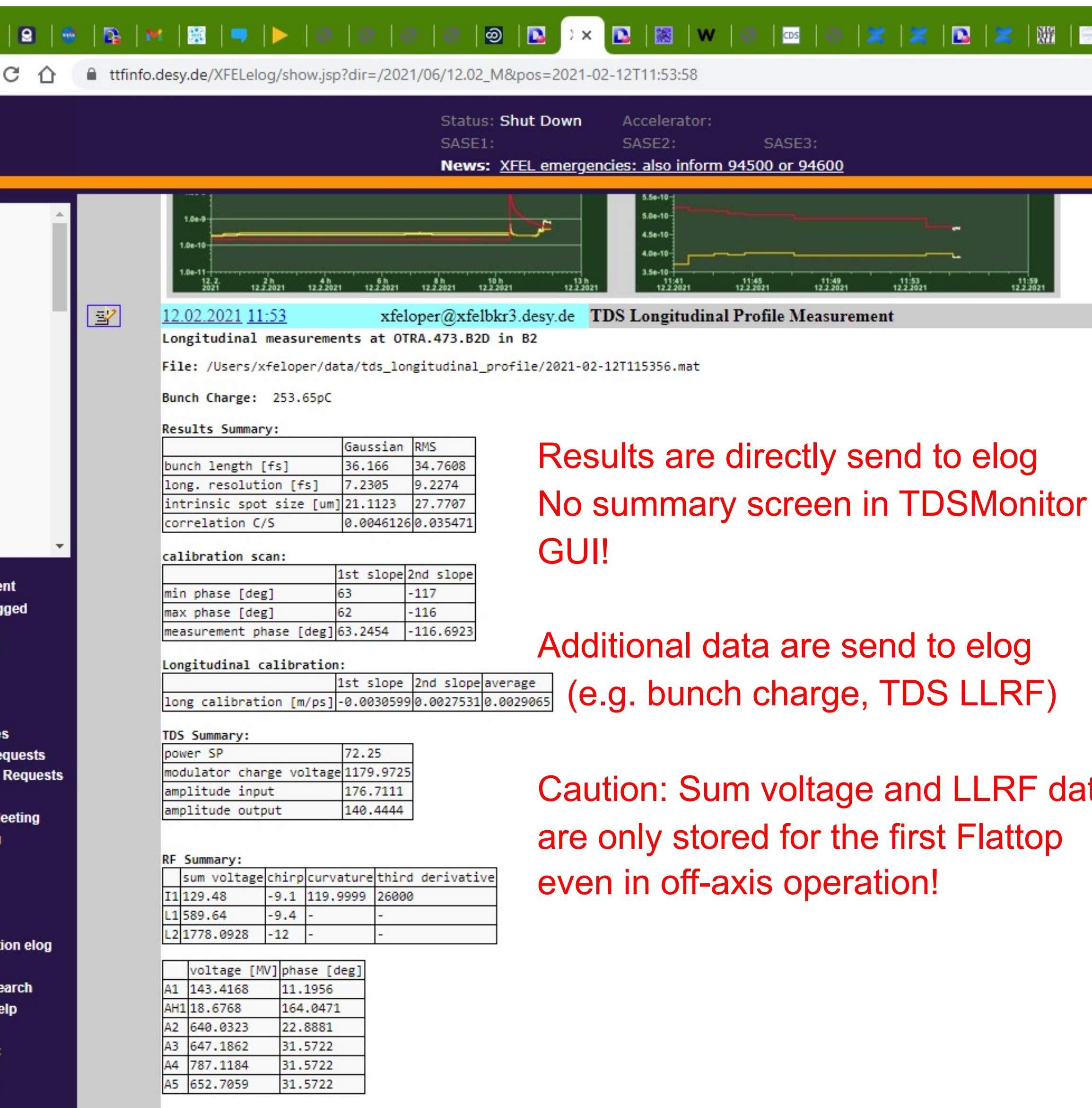
TDS Measurements Analysis



ttfinfo.desy.de/XFELelog/show.jsp?dir=/2021/06/12.02_M&pos=2021-02-12T11:53:58

Status: Shut Down Accelerator:
SASE1: SASE2: SASE3:
News: XFEL emergencies: also inform 94500 or 94600

12.02.2021 11:53 xfeloper@xfelbkr3.desy.de **TDS Longitudinal Profile Measurement**

Longitudinal measurements at OTRA.473.B2D in B2

File: /Users/xfeloper/data/tds_longitudinal_profile/2021-02-12T115356.mat

Bunch Charge: 253.65pC

Results Summary:

	Gaussian	RMS
bunch length [fs]	36.166	34.7608
long. resolution [fs]	7.2305	9.2274
intrinsic spot size [um]	21.1123	27.7707
correlation C/S	0.0046126	0.035471

calibration scan:

	1st slope	2nd slope
min phase [deg]	63	-117
max phase [deg]	62	-116
measurement phase [deg]	63.2454	-116.6923

Longitudinal calibration:

	1st slope	2nd slope	average
long calibration [m/ps]	-0.0030599	0.0027531	0.0029065

TDS Summary:

power SP	72.25
modulator charge voltage	1179.9725
amplitude input	176.7111
amplitude output	140.4444

RF Summary:

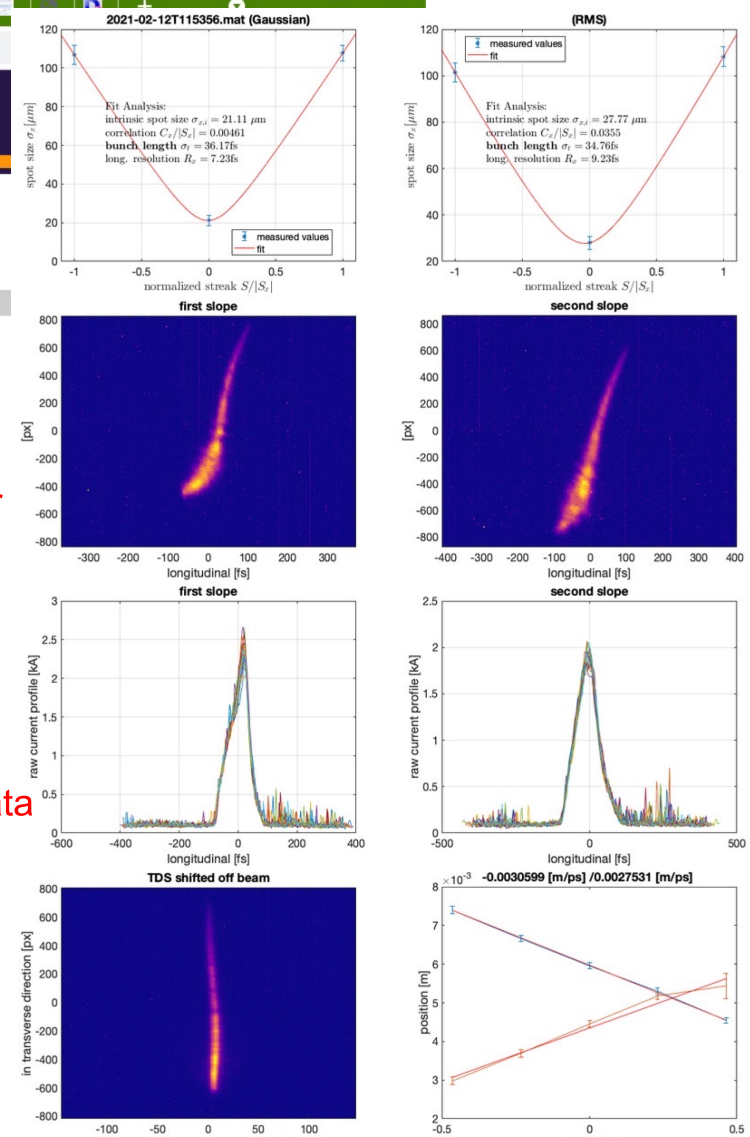
	sum voltage	chirp	curvature	third derivative
I1	129.48	-9.1	119.9999	26000
L1	589.64	-9.4	-	-
L2	1778.0928	-12	-	-

	voltage [MV]	phase [deg]
A1	143.4168	11.1956
AH1	18.6768	164.0471
A2	640.0323	22.8881
A3	647.1862	31.5722
A4	787.1184	31.5722
A5	652.7059	31.5722

Results are directly send to elog
No summary screen in TDSMonitor GUI!

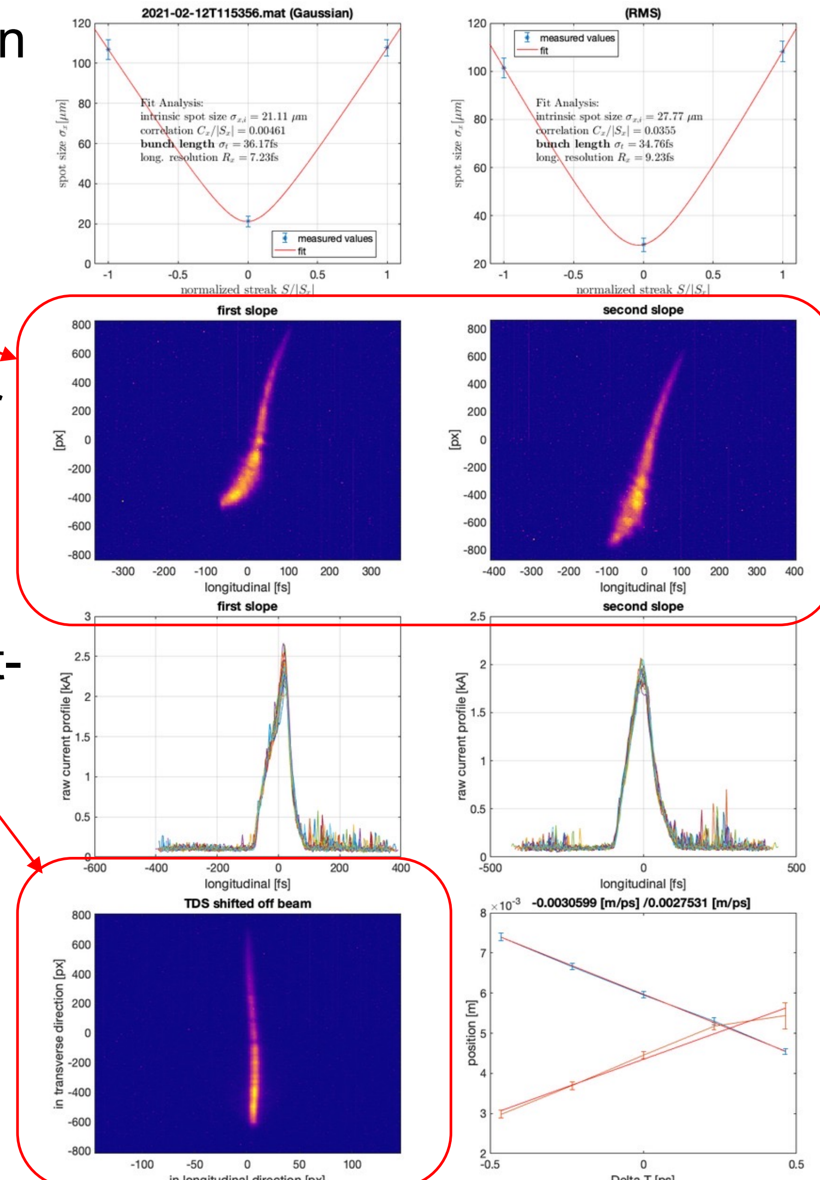
Additional data are send to elog
(e.g. bunch charge, TDS LLRF)

Caution: Sum voltage and LLRF data are only stored for the first Flattop even in off-axis operation!



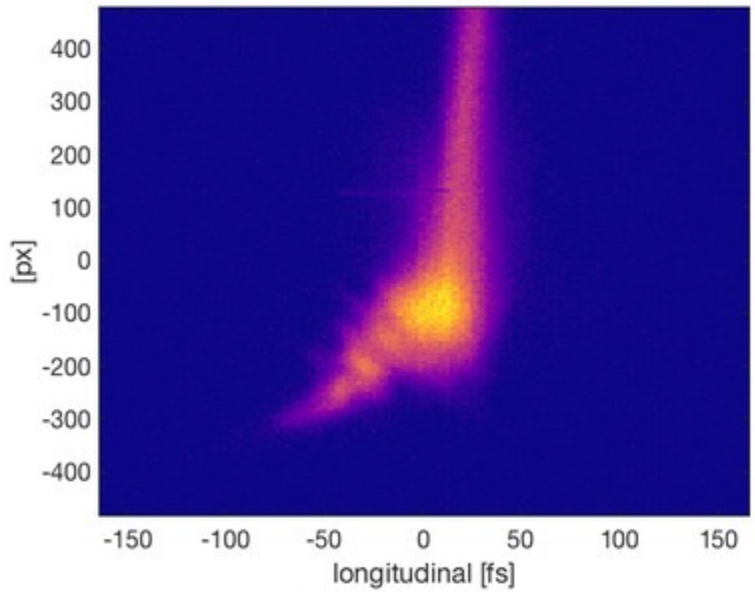
Is the compression properly setup?

- Bunch length at B2 should be between 30-40fs for good SASE (250pC)
- Longitudinal PS should look similar to the example
- If unstreaked beam is “tilted” consider checking dispersion between injector and linac
- A strong asymmetry between the spot-size of both “zero-crossings” is another indication for beam tilts



European XFEL

Thank You for Your Attention!



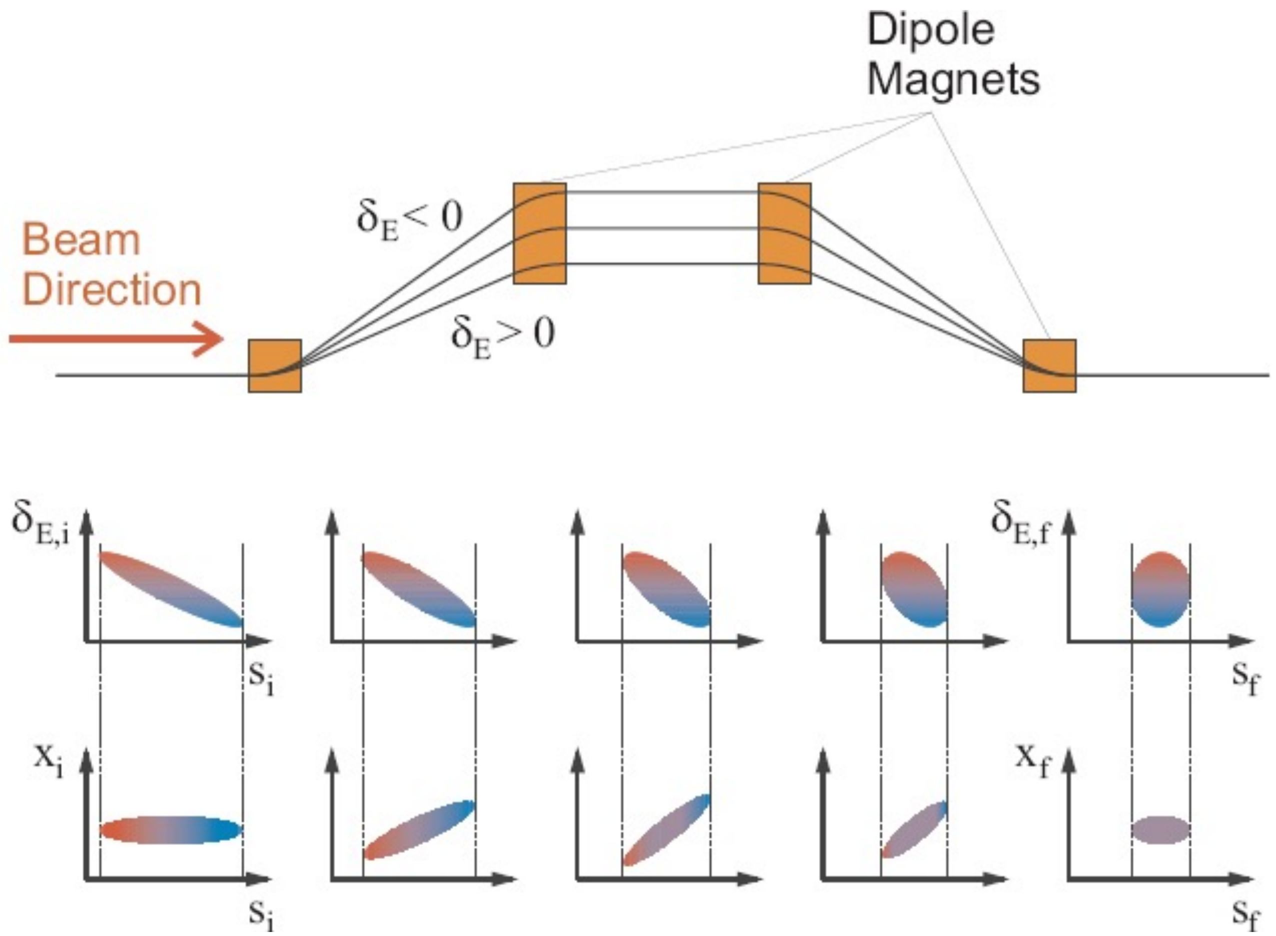
Questions?

Literature:

- Igor Zagorodnov and Martin Dohlus, “Semianalytical modeling of multistage bunch compression with collective effects” Phys. Rev. ST Accel. Beams 14, 014403 – Published 13 January 2011
- ICFA Beam Dynamics Newsletter No. 38, (http://icfa-usa.jlab.org/archive/newsletter/icfa_bd_nl_38.pdf)
- Various PhD theses:
  Frank Stulle (http://www-library.desy.de/cgi-bin/showprep.pl?desy-thesis-04-041),
  BB (http://www-library.desy.de/cgi-bin/showprep.pl?desy-thesis-07-040), …

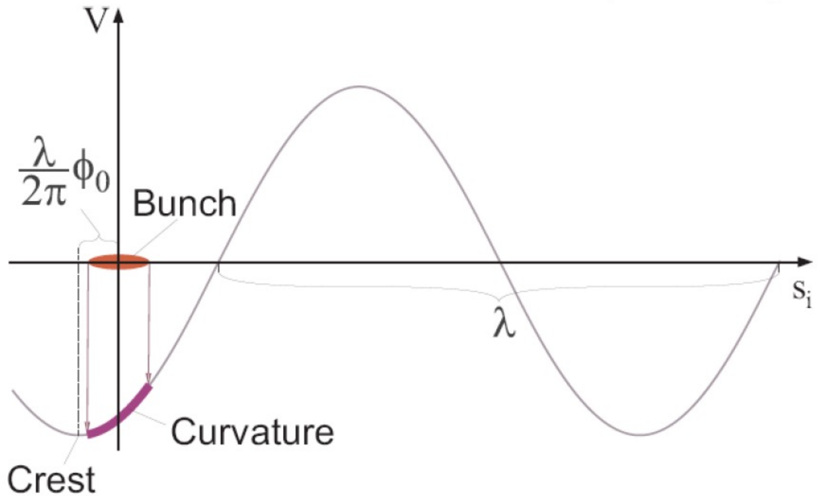
In-house Experts: Martin Dohlus, Igor Zagorodnov, Torsten Limberg, BB

Bunch Compression – with Formulas



$$\Delta s = R_{56} \cdot \delta + T_{566} \cdot \delta^2 + U_{5666} \cdot \delta^3 + \cdots \quad \text{with} \quad \delta = \frac{E - E_0}{E_0}$$

Energy Chirp Generation



$$E(s) = eV\cos\left(\varphi + \frac{2\pi}{\lambda}s\right) + E_0$$

$$= E_0 + eV\left(\cos(\varphi) - \frac{2\pi}{\lambda}\sin(\varphi)s - \frac{2\pi^2}{\lambda}\cos(\varphi)s^2 + \cdots\right)$$

$$\delta = \frac{E(s) - E(0)}{E(0)}$$

$$= -\frac{2\pi eV}{E\lambda}\sin(\varphi)s - \frac{2\pi^2}{E\lambda^2}\cos(\varphi)s^2 + \cdots$$

$$\approx As + Bs^2$$

$$A = -\frac{2\pi eV}{E\lambda}\sin(\varphi)$$

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Linear Compression

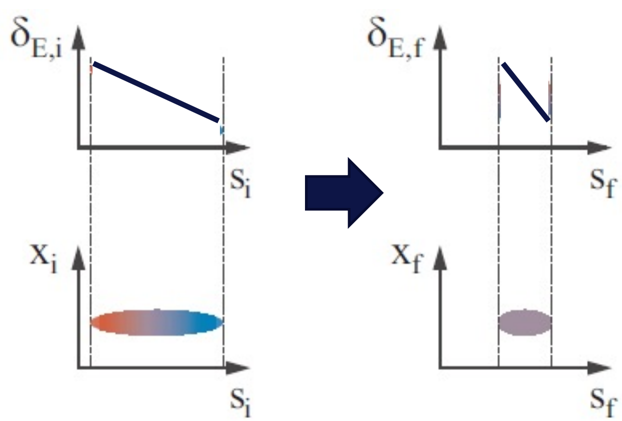
$$\delta(s_{\text{initial}}) = A s_{\text{initial}}$$

$$s_{\text{final}} = s_{\text{initial}} + R_{56}\delta$$

$$s_{\text{final}} = (1 + AR_{56}) s_{\text{initial}}$$

$$\sigma_{s_{\text{final}}} = \sqrt{(1 + AR_{56})^2 \sigma^2_{s_{\text{initial}}}}$$

$$= |1 + AR_{56}|\, \sigma_{s_{\text{initial}}} \qquad = \frac{\sigma_{s_{\text{initial}}}}{C}$$



Full compression at $(1 + AR_{56}) = 0$, however C = 1/0 !

Linear Compression with Uncorrelated Energy Spread

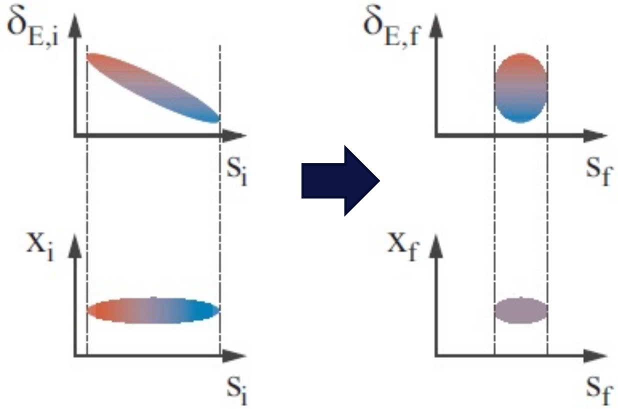
each particle *i* has an individual “random” energy offset

$$\delta(s_{\mathrm{initial}}, i) = A s_{\mathrm{initial}} + \delta^i$$

$$s_{\mathrm{final}} = s_{\mathrm{initial}} + R_{56}\delta$$

$$s_{\mathrm{final}} = (1 + A R_{56}) s_{\mathrm{initial}} + R_{56}\delta^i$$

$$\sigma_{s_{\mathrm{final}}} = \sqrt{(1 + A R_{56})^2 \sigma^2_{s_{\mathrm{initial}}} + R^2_{56}\sigma^2_{\delta^i}}$$



$$\text{if } (1 + A R_{56}) = 0$$

$$\sigma^{\mathrm{min}}_{s_{\mathrm{final}}} \approx |R_{56}|\,\sigma_{\delta^i}$$

Typically the “full” compression is avoided…

Simple Compression Setup

$$A = -\frac{E_1 k_1}{E}\sin(\varphi)$$

$$\sigma_{\text{final}} = |1 + AR_{56}|\,\sigma_{\text{initial}}$$

$$E = E_0 + E_1\cos(\varphi)$$

$$\Rightarrow \qquad \varphi = \arctan\left(-\frac{E}{E-E_0}\frac{\left(\frac{\sigma_{\text{final}}}{\sigma_{\text{initial}}}-1\right)}{k_1 R_{56}}\right)$$

$$E_1 = \frac{E-E_0}{\cos(\varphi)}$$

Is this Ok?

Non-linear Compression

$$s_{\text{final}} = s_{\text{initial}} + R_{56}\delta + T_{566}\delta^2 + \cdots$$

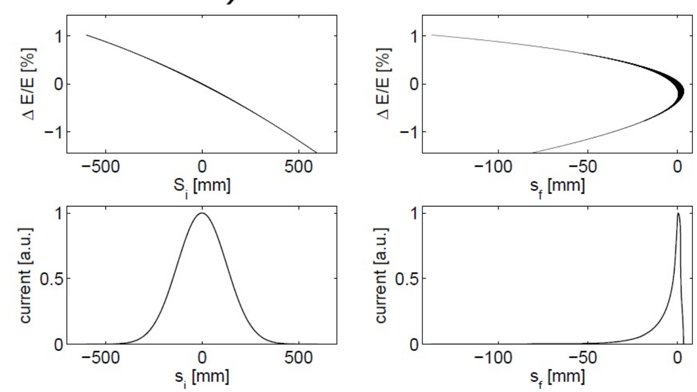
$$\delta = A s_{\text{initial}} + B s_{\text{initial}}^2 + \cdots$$

$$\delta(s_{\text{initial}}) = \frac{-E_1 \sin(\varphi) k_1 s_{\text{initial}} - E_1 \cos(\varphi)\frac{k_1^2}{2} s_{\text{initial}}^2}{E_0 + E_1 \cos(\varphi)}$$

$$s_{\text{final}} = \frac{R_{56}}{E}\left(-E_1 \sin(\varphi) k_1 s_{\text{initial}} - E_1 \cos(\varphi)\frac{k_1^2}{2} s_{\text{initial}}^2\right) + \frac{T_{566}}{E^2} E_1^2 \sin^2(\varphi) k_1^2 s_{\text{initial}}^2 + s_{\text{initial}}$$

Can we tune the T_{566}-term to compensate the E_1 quadratic-term?

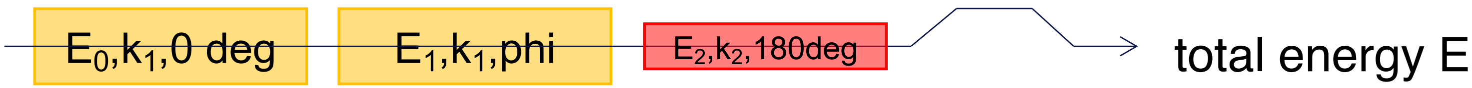
No since $T_{566} \approx -\frac{3}{2} R_{56}$



This is NOT Ok!

European XFEL

Linarised Compression



$$s_{\text{final}} = s_{\text{initial}} + R_{56}\delta + T_{566}\delta^2 + \cdots$$

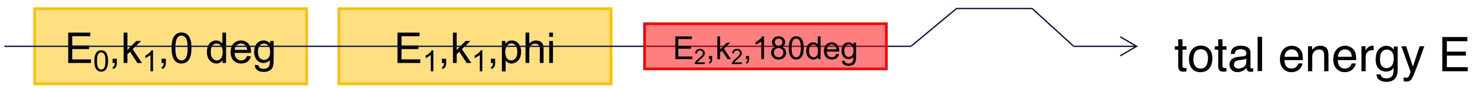
$$\delta = A s_{\text{initial}} + B s_{\text{initial}}^2 + \cdots$$

$$\delta(s_{\text{initial}}) = \frac{-E_1 \sin(\varphi) k_1 s_{\text{initial}} - E_1 \cos(\varphi) \frac{k_1^2}{2} s_{\text{initial}}^2 + E_2 \frac{k_2^2}{2} s_{\text{initial}}^2}{E_0 + E_1 \cos(\varphi) - E_2}$$

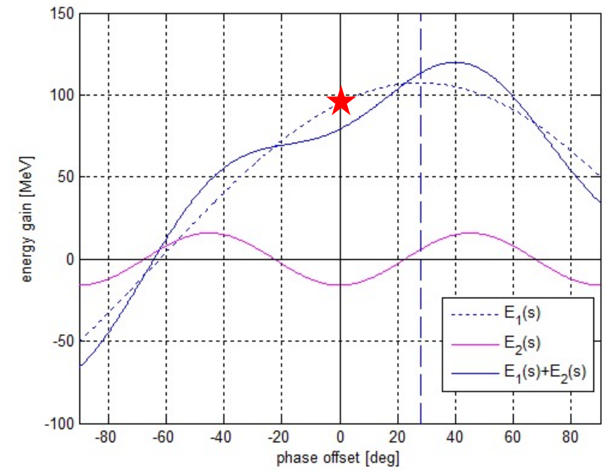
$$s_{\text{final}} = \frac{R_{56}}{E}\left(-E_1 \sin(\varphi) k_1 s_{\text{initial}} - E_1 \cos(\varphi) \frac{k_1^2}{2} s_{\text{initial}}^2 + E_2 \frac{k_2^2}{2} s_{\text{initial}}^2\right) + \frac{T_{566}}{E^2} E_1^2 \sin^2(\varphi) k_1^2 s_{\text{initial}}^2 + s_{\text{initial}}$$

$$E_2 = \left(E_1 \cos(\varphi) + 3\frac{E_1^2}{E}\sin^2(\varphi)\right)\frac{k_1^2}{k_2^2}$$

Energy Compensation



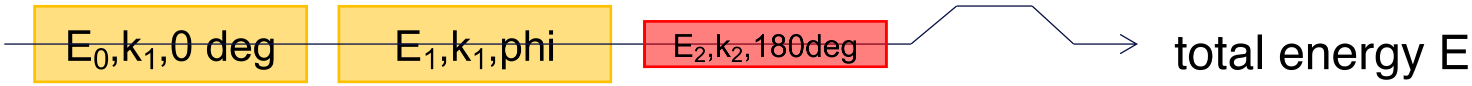
$$E_2 = \left(E_1 \cos(\varphi) + 3\frac{E_1^2}{E} \sin^2(\varphi) \right) \frac{k_1^2}{k_2^2}$$



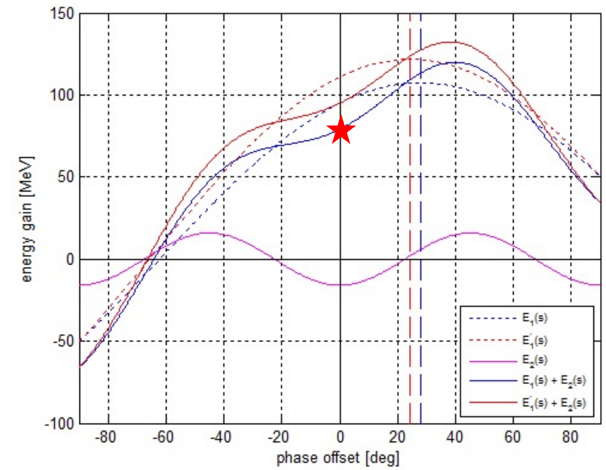
$$E_1 \sin(\varphi) = E_1' \sin(\varphi')$$
$$E_1 \cos(\varphi) + E_2 = E_1' \cos(\varphi')$$

Compensation of energy loss is required while the slope must be maintained.

Energy Compensation



$$E_2 = \left(E_1 \cos(\varphi) + 3\frac{E_1^2}{E} \sin^2(\varphi) \right) \frac{k_1^2}{k_2^2}$$



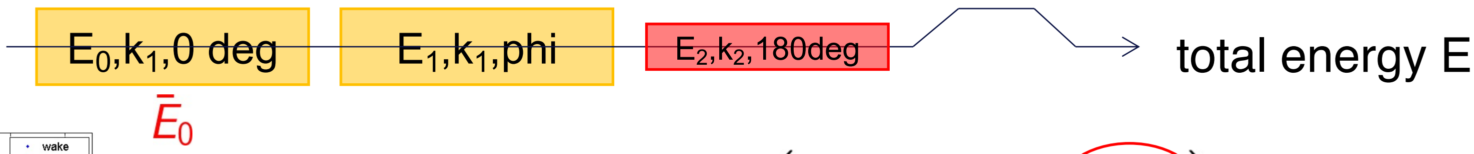
$$E_1 \sin(\varphi) = E_1' \sin(\varphi')$$
$$E_1 \cos(\varphi) + E_2 = E_1' \cos(\varphi')$$

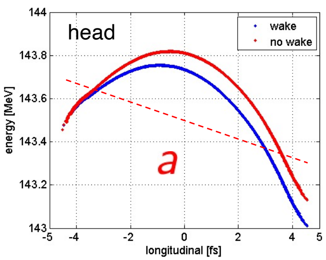
$$\Rightarrow \quad \varphi' = \arctan\left(\frac{E_1 \sin(\varphi)}{E_1 \cos(\varphi) + E_2} \right)$$

$$E_1' = E_1 \frac{\sin(\varphi)}{\sin(\varphi')}$$

Compensation of energy loss is required while the slope must be maintained.

(Almost) General Solution for Single Stage BC





$$\varphi = \arctan\left(-\frac{E}{E-E_0}\frac{\left(\frac{\sigma_{\text{final}}}{\sigma_{\text{initial}}}-1-aR_{56}\right)}{k_1 R_{56}}\right)$$

$$E_1 = \frac{E-E_0}{\cos(\varphi)}$$

$$E_2 = \left(E_1\cos(\varphi)+\bar{E}_0+3\frac{E_1^2}{E}\sin^2(\varphi)\right)\frac{k_1^2}{k_2^2}$$

$$\varphi' = \arctan\left(\frac{E_1\sin(\varphi)}{E_1\cos(\varphi)+E_2}\right)$$

$$E_1' = E_1\frac{\sin(\varphi)}{\sin(\varphi')}$$

If x-band is not operated “anti-on-crest” an additional linear compression term plays a role.

The End