Bunch Compression Operation at the European XFEL

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Operator Training
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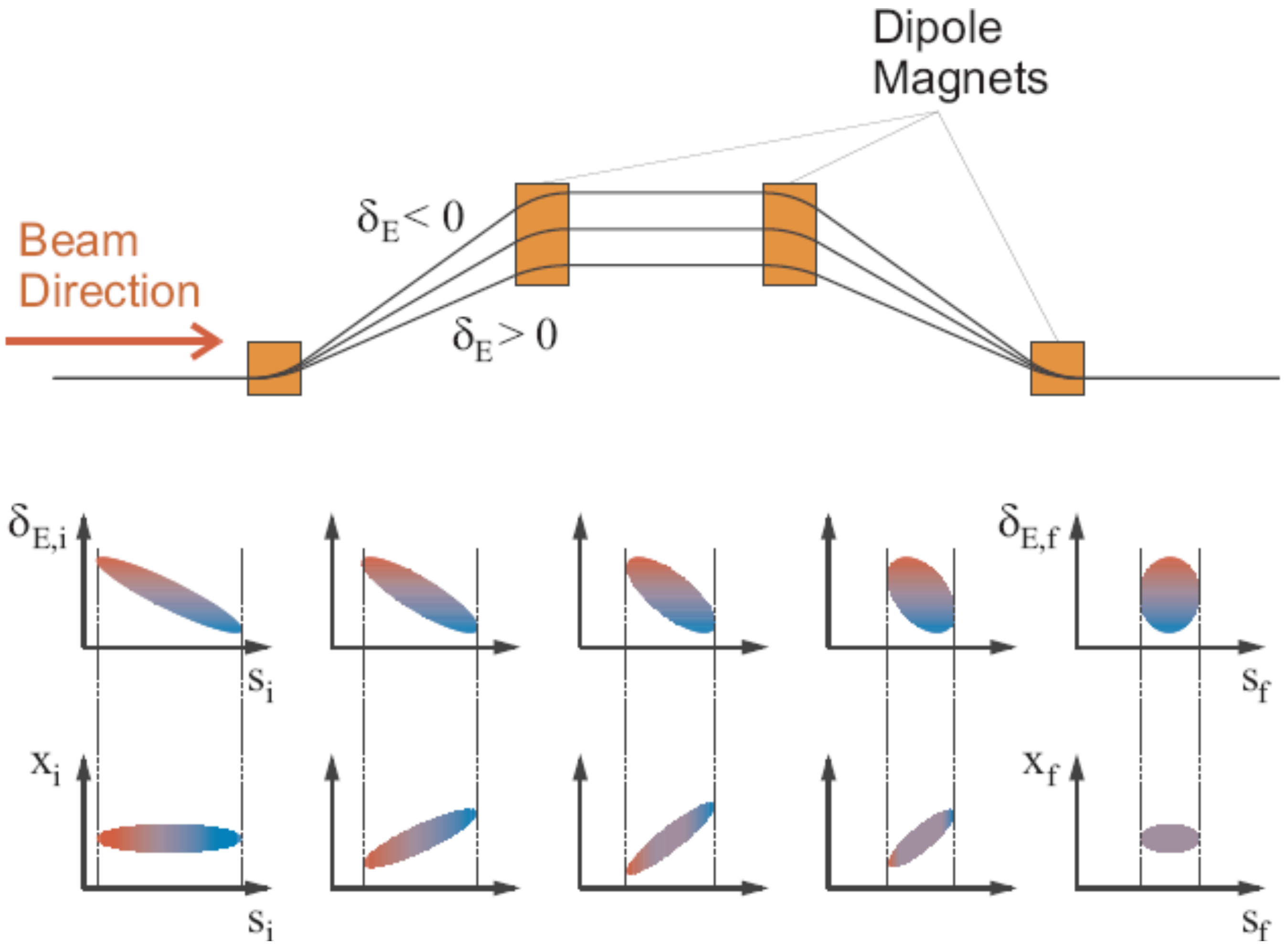
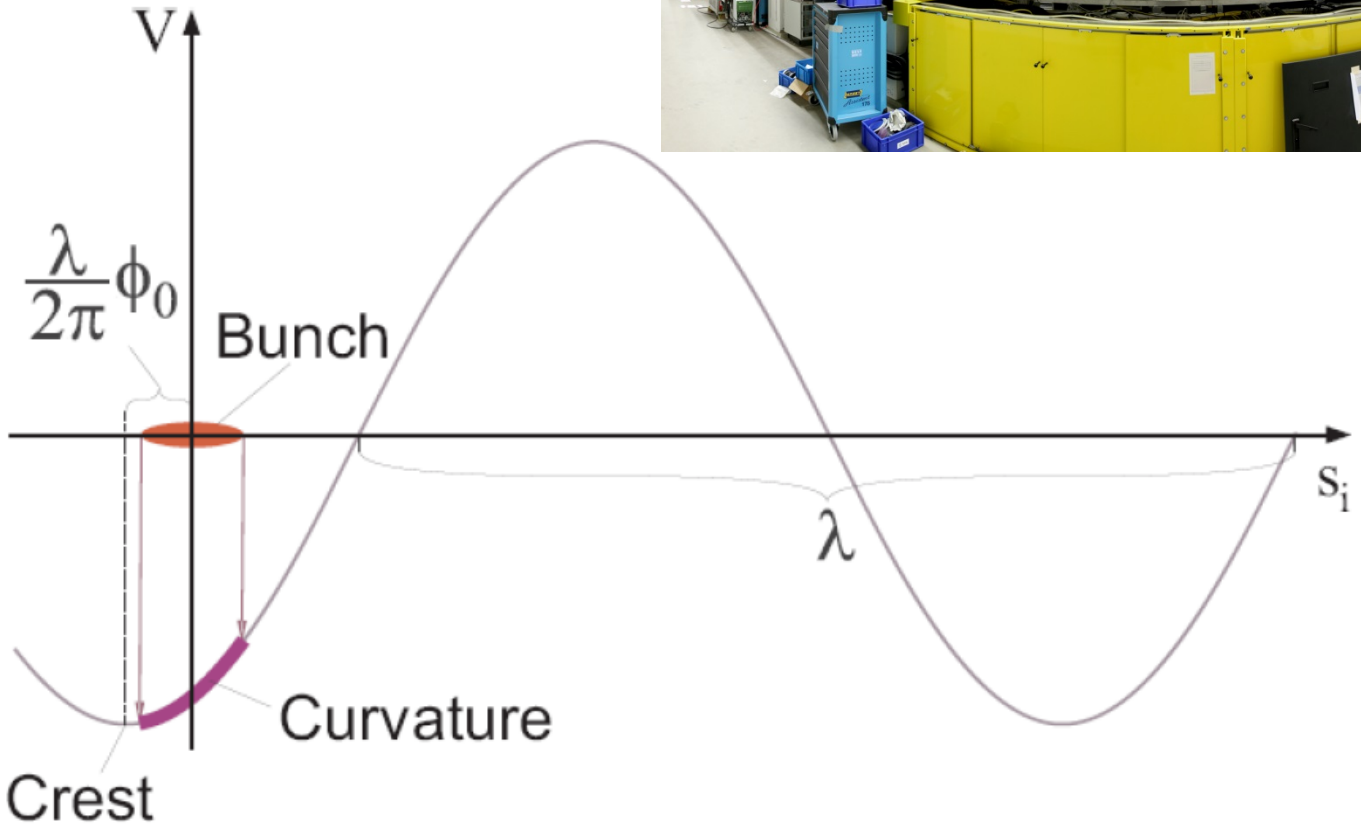
FEL Performance

- 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



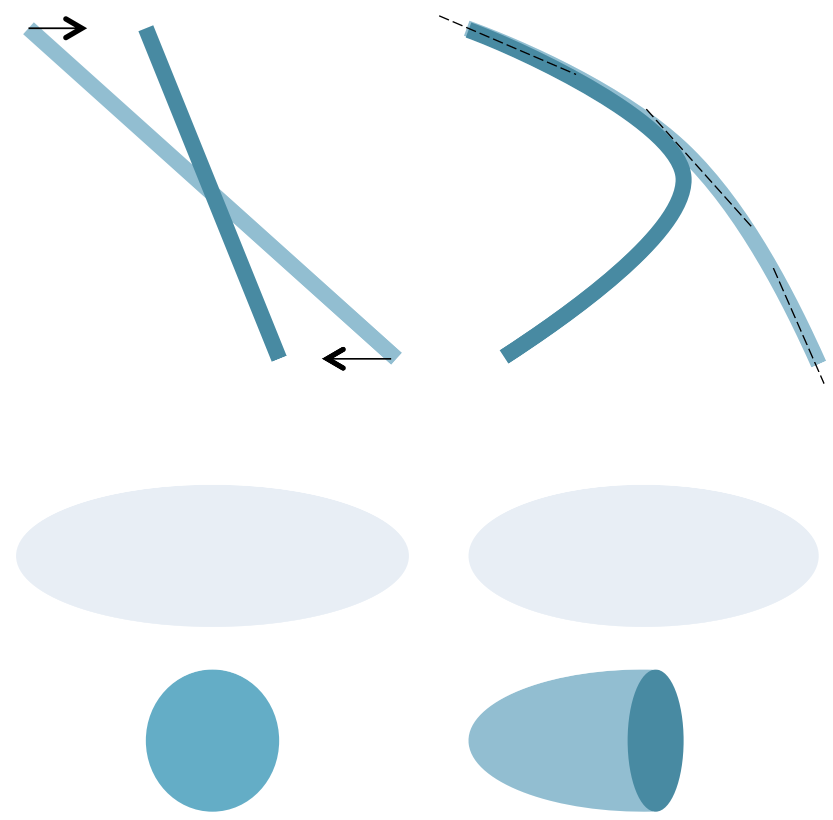
Energy Chirp Generation



“Non-linear” Compression

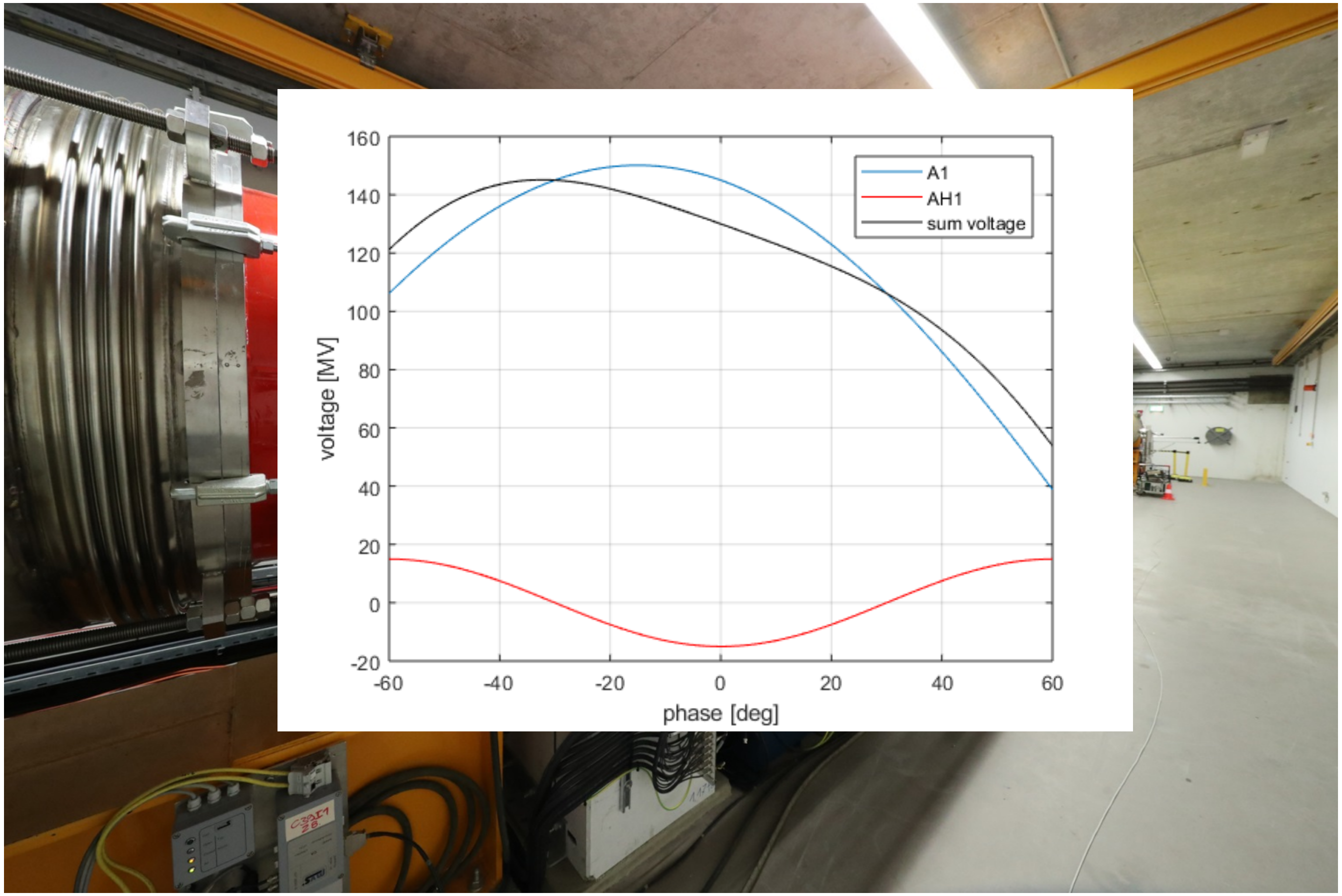
Linear Compression:

Non-Linear Compression:



Phase Space Linearisation

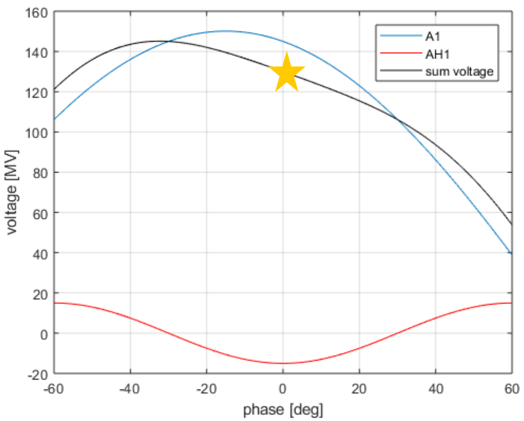
- Higher harmonic RF system is used to remove non-linear chirp
- 3rd harmonic (3.9GHz) at XFEL and FLASH



Sum Voltage

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

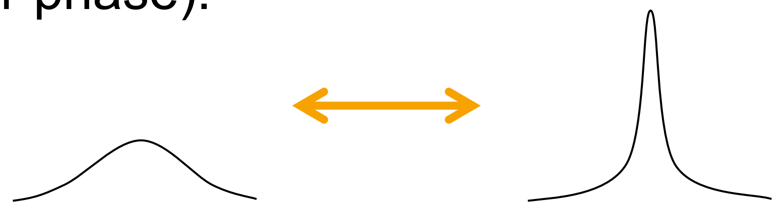
- RF parameters can be directly calculated from the Taylor coefficients (energy, chirp, curvature) at the beam position



- 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)

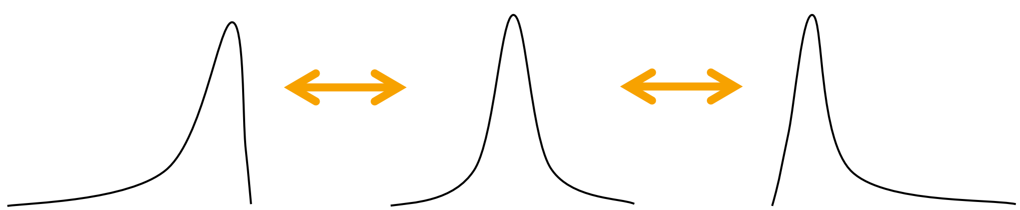
Sum Voltage Effects

- Chirp (mostly A1 phase):

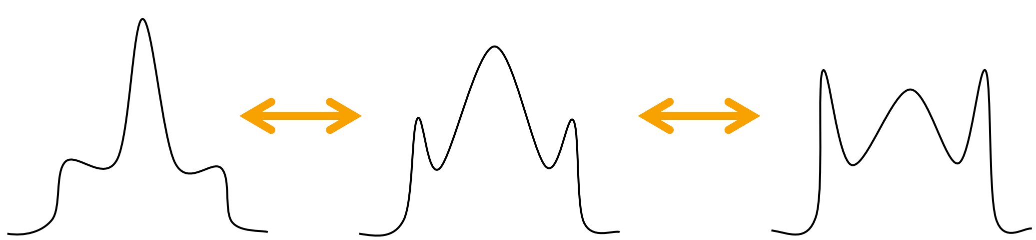


Current profiles

- Curvature (mostly AH1 voltage):



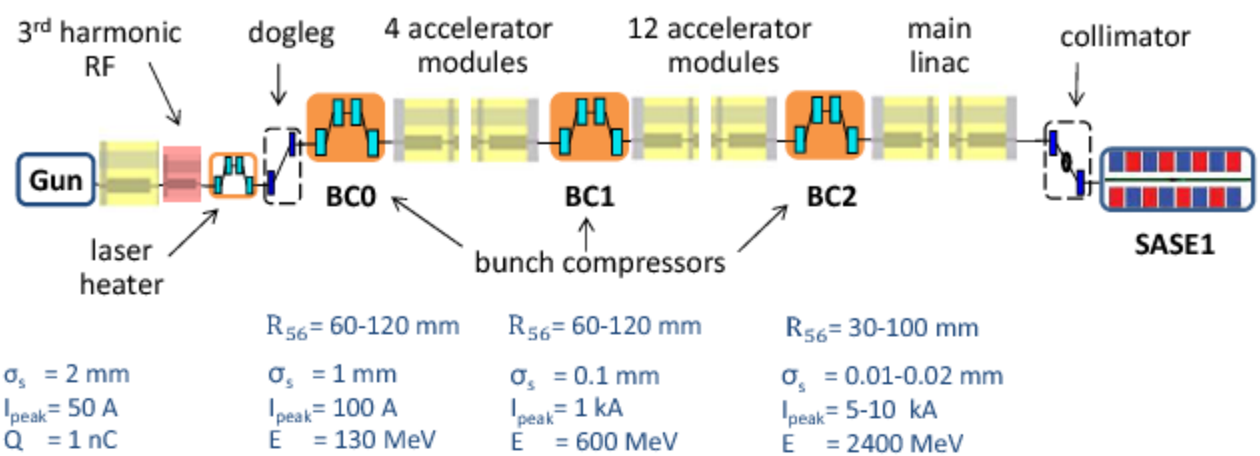
- Third Order “Skewness” (AH1 voltage and phase):



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

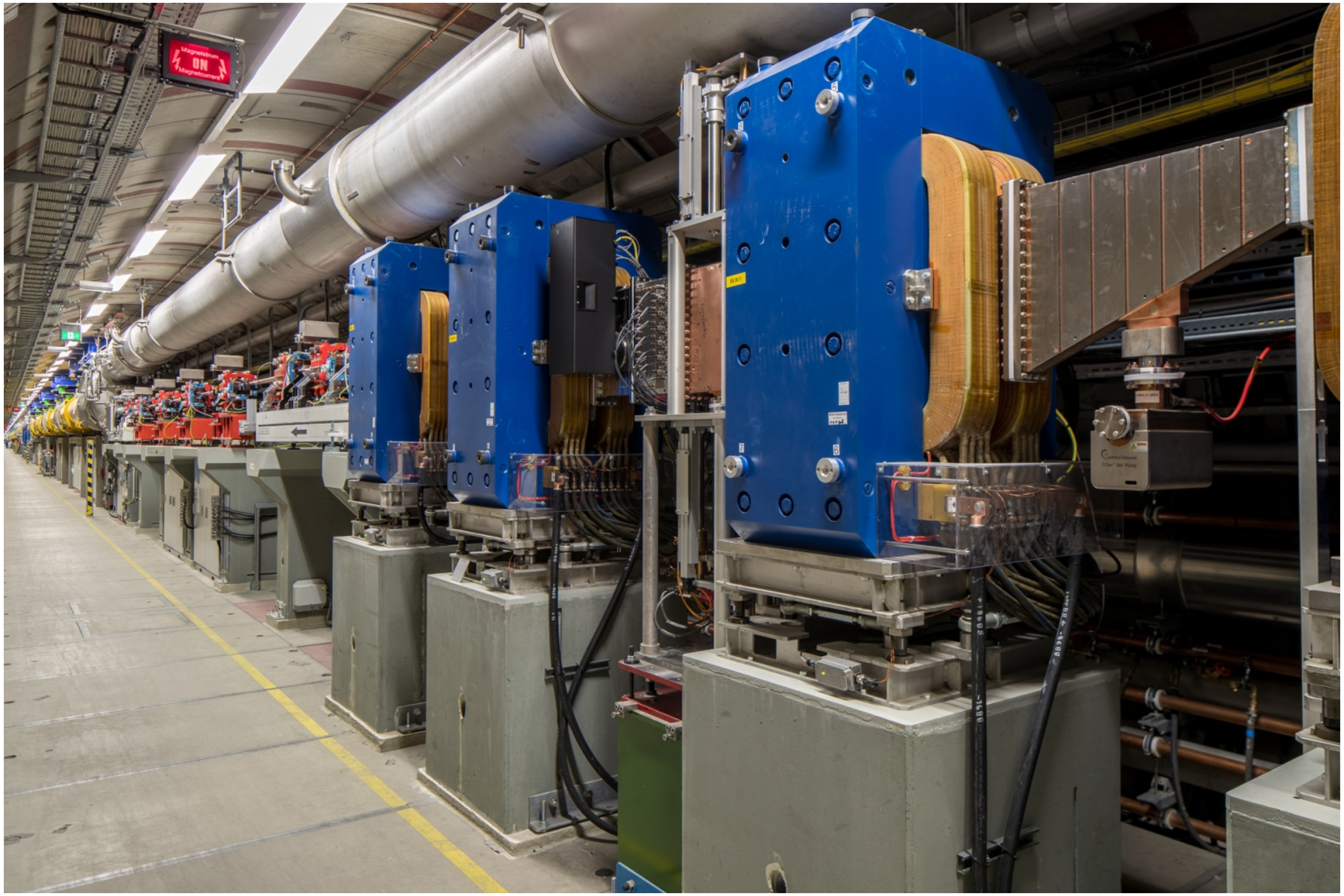
=> Multi-stage compression



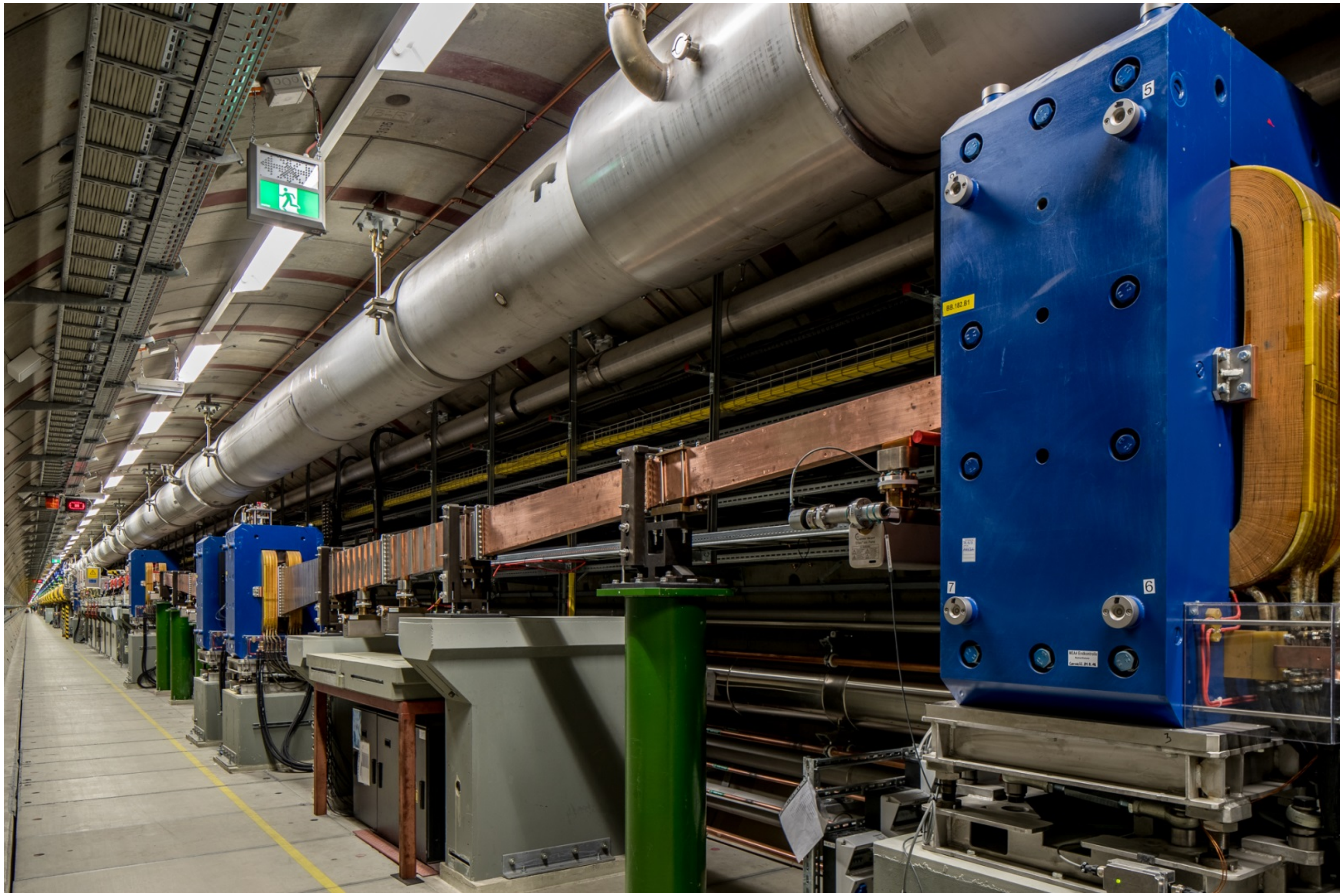
European XFEL

DESY

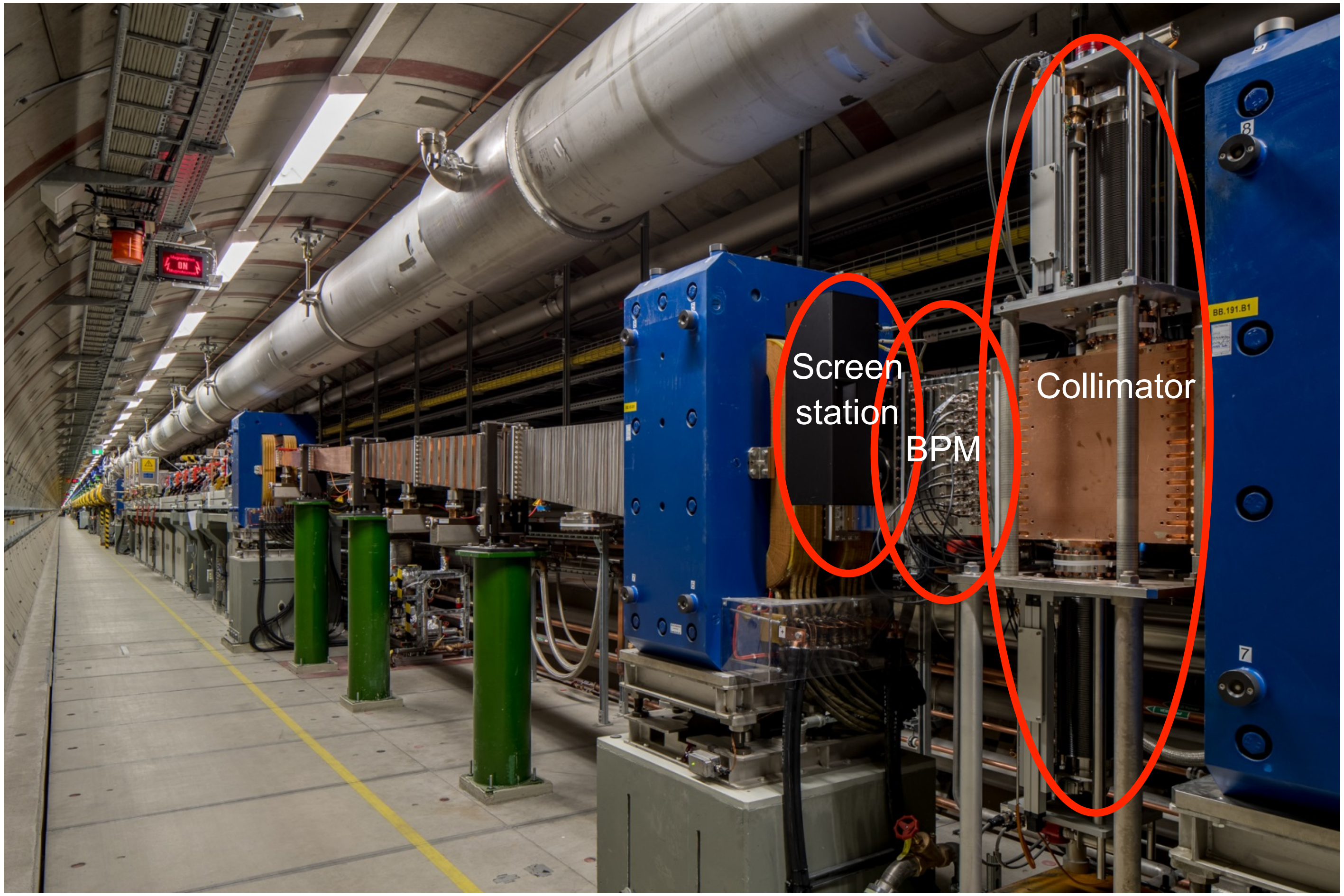
BC0



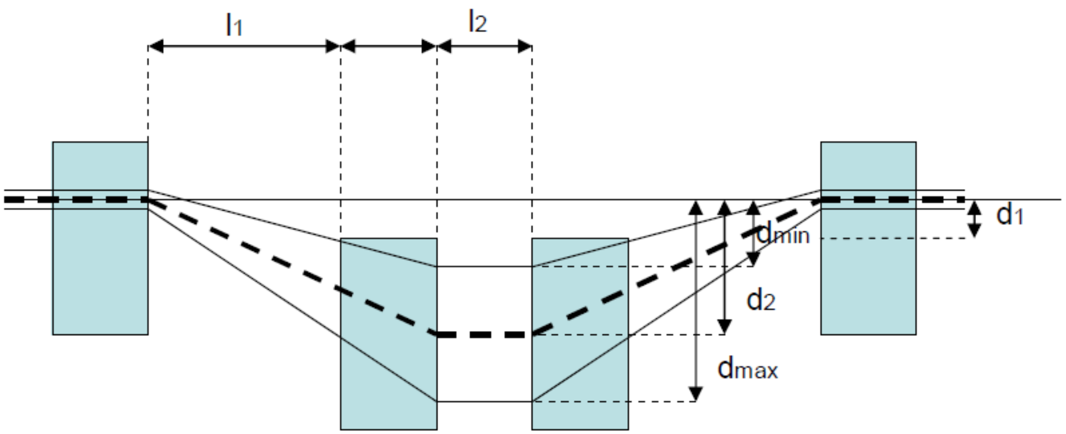
BC1



BC1

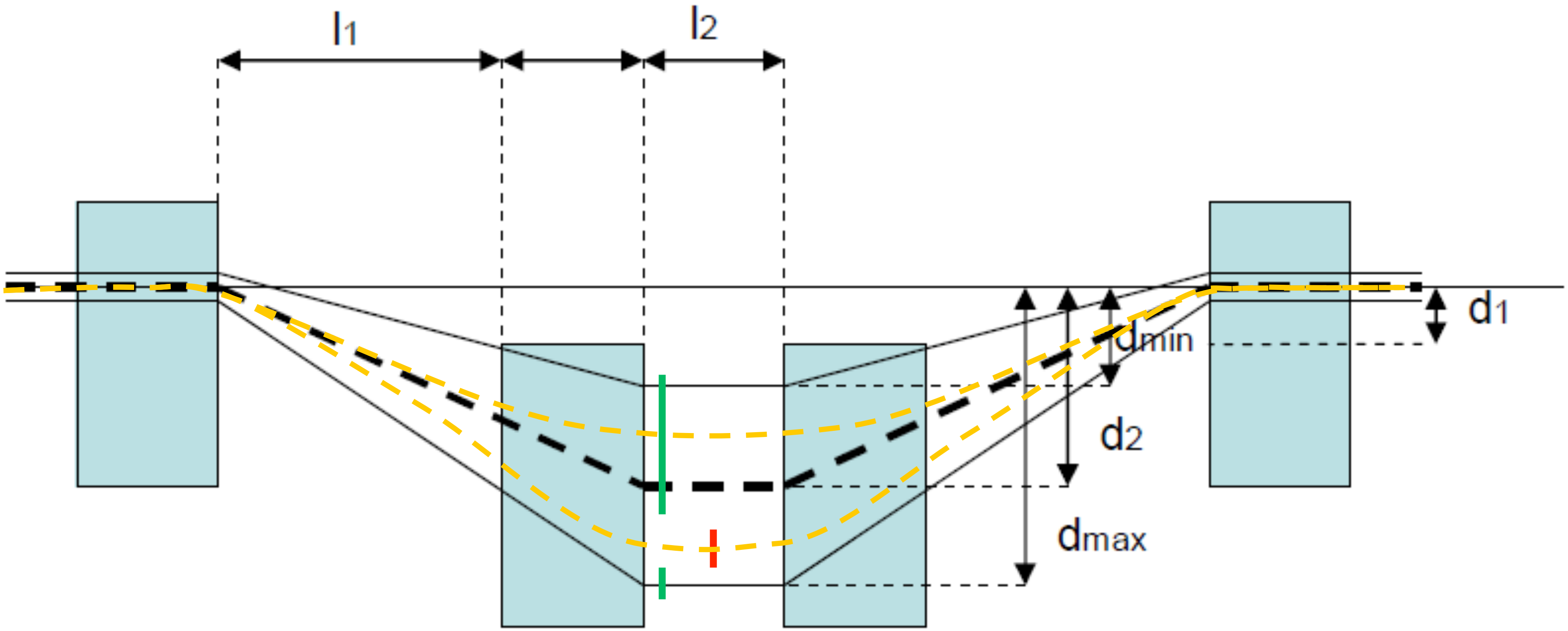


XFEL BC Overview



	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

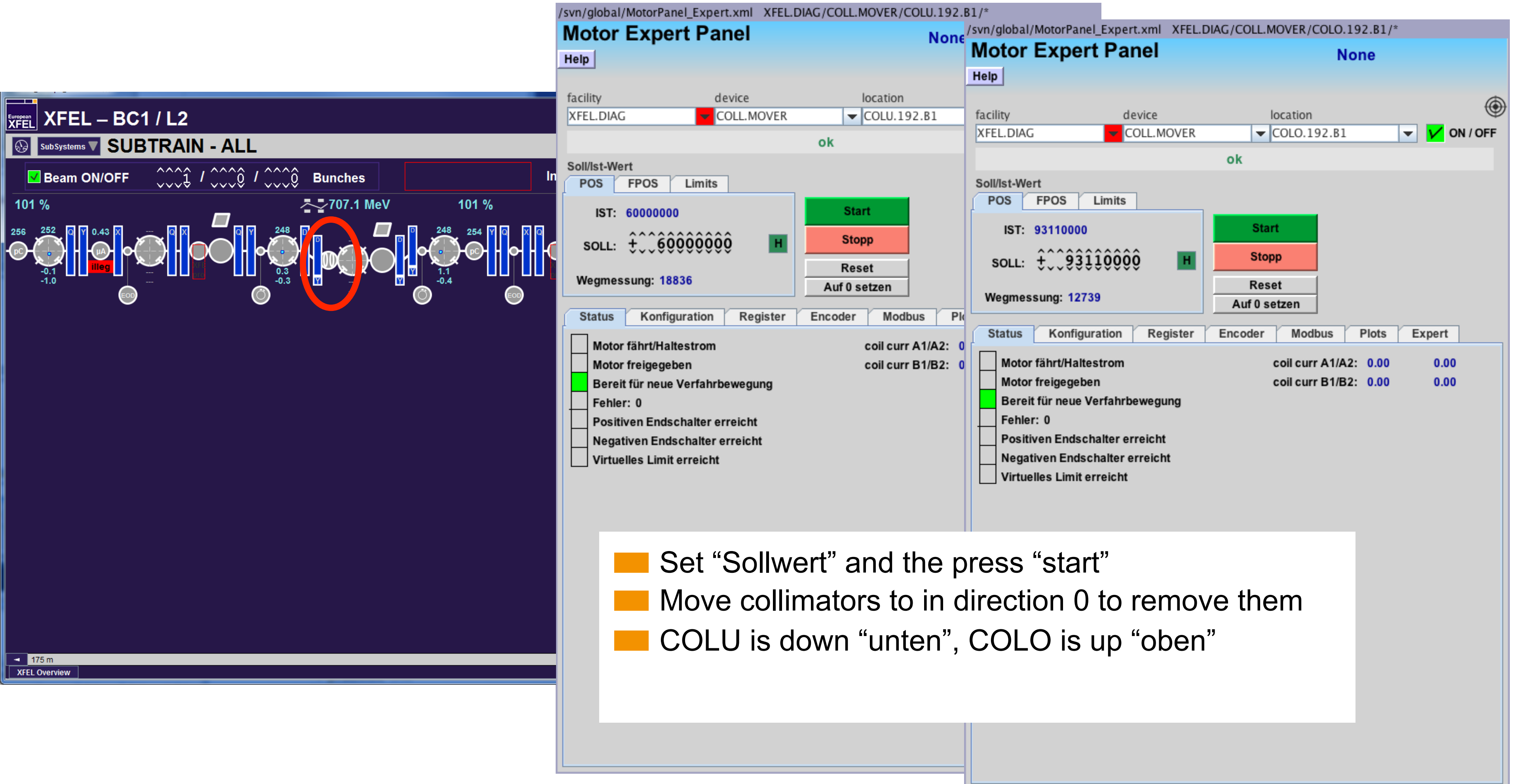
Chamber Overview



Screen
Collimator

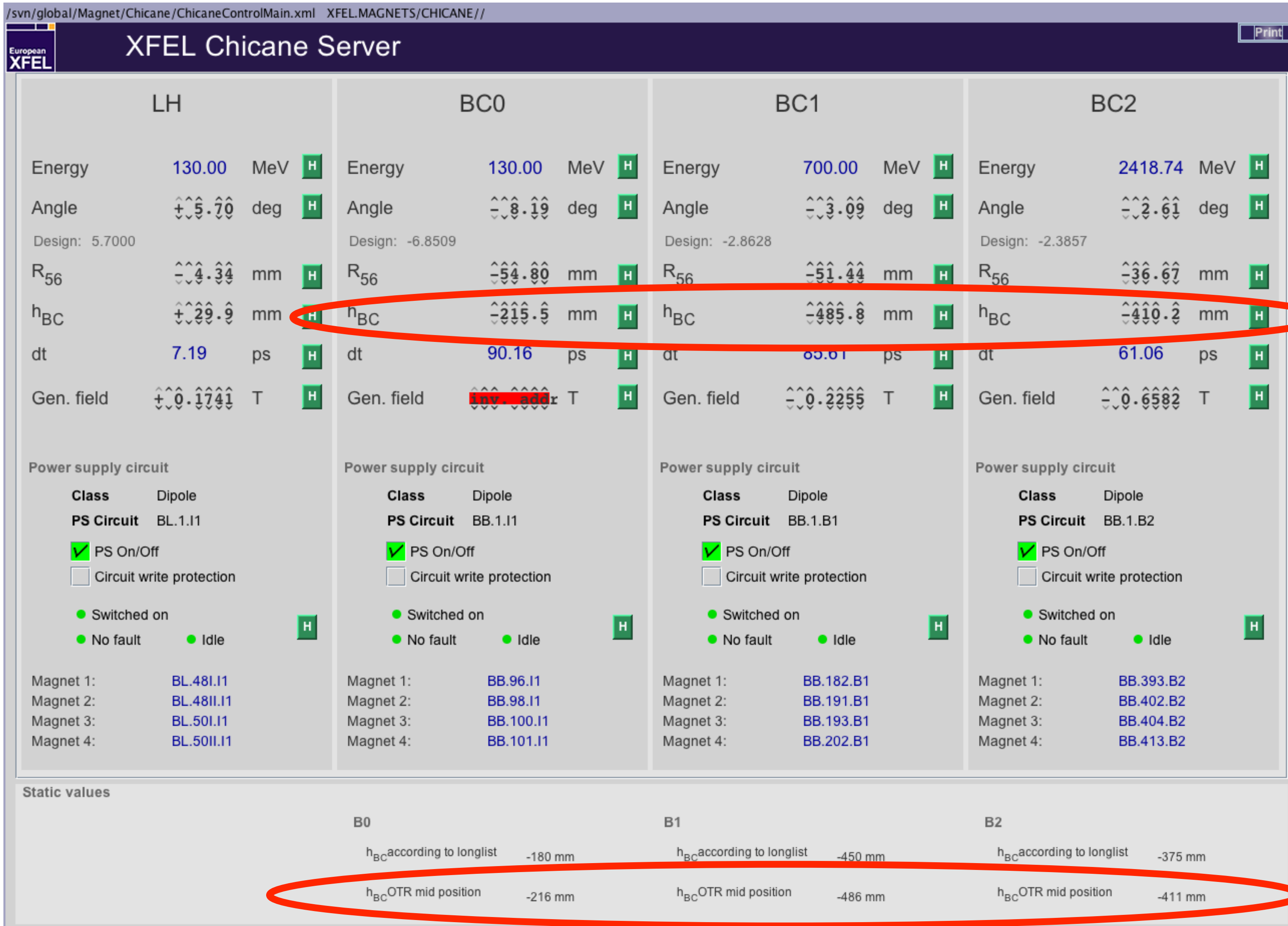
Not to scale!

BC Collimator Control

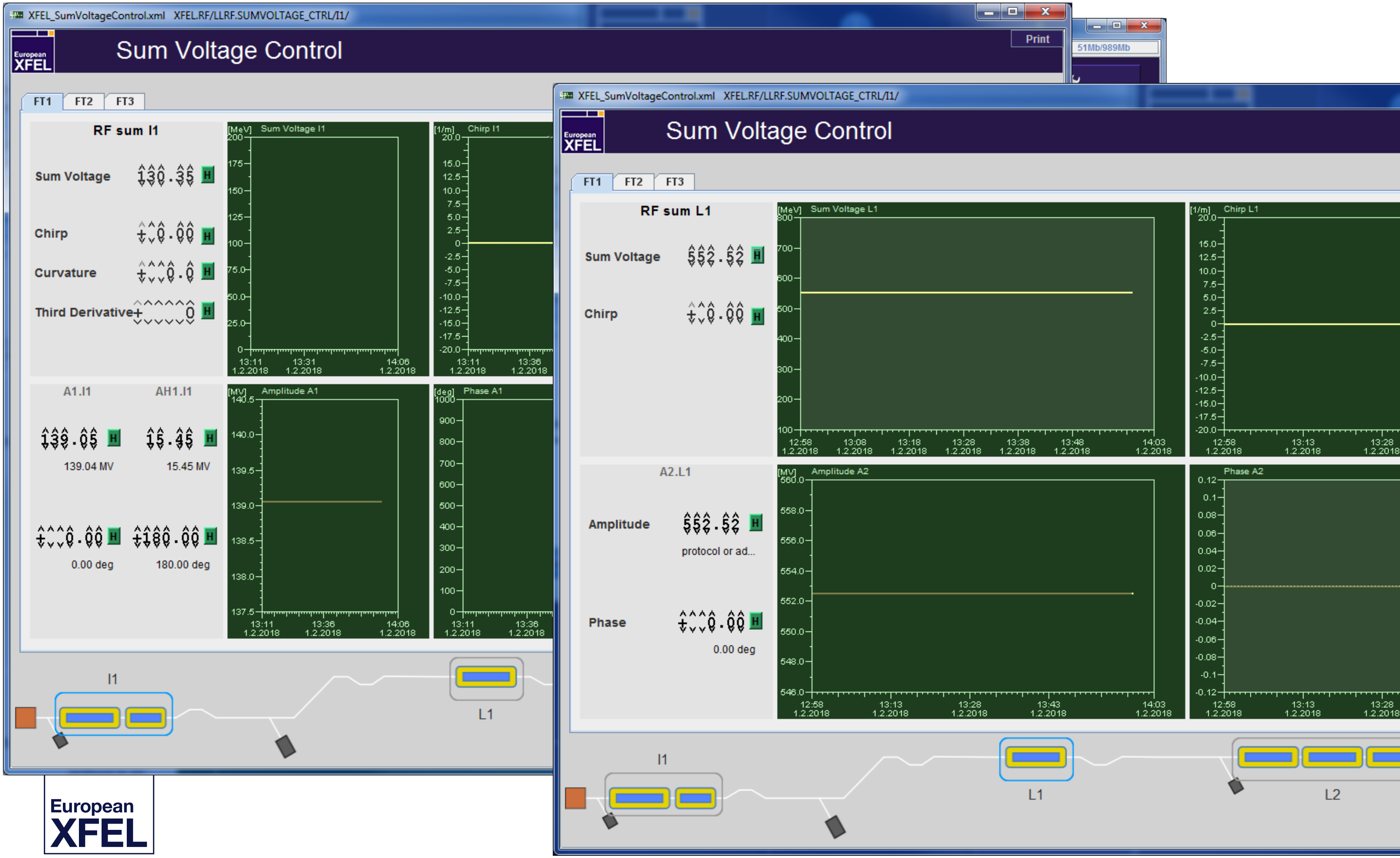


- Set “Sollwert” and the press “start”
- Move collimators to in direction 0 to remove them
- COLU is down “unten”, COLO is up “oben”

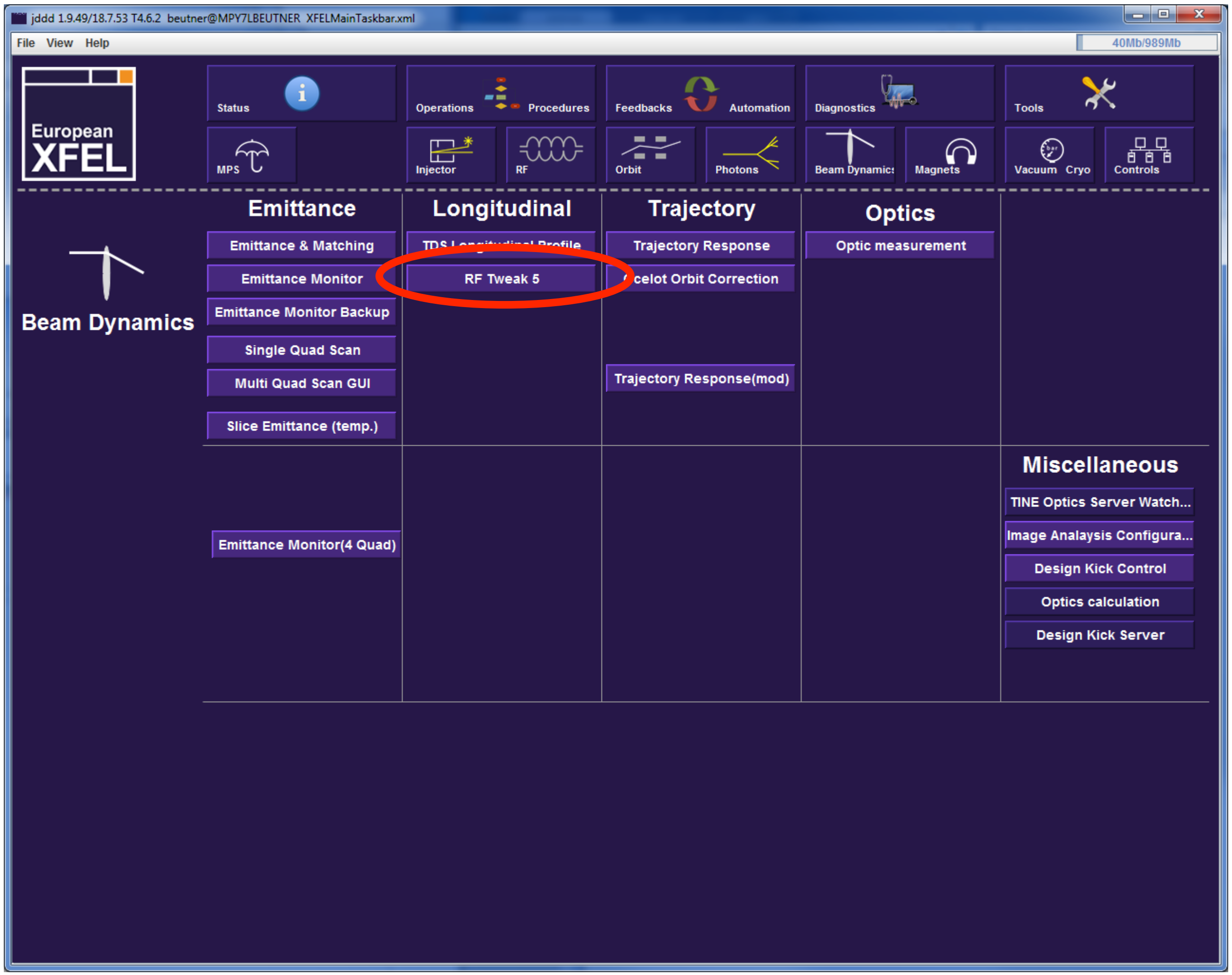
Dipole Setup



RF Setup and Tuning

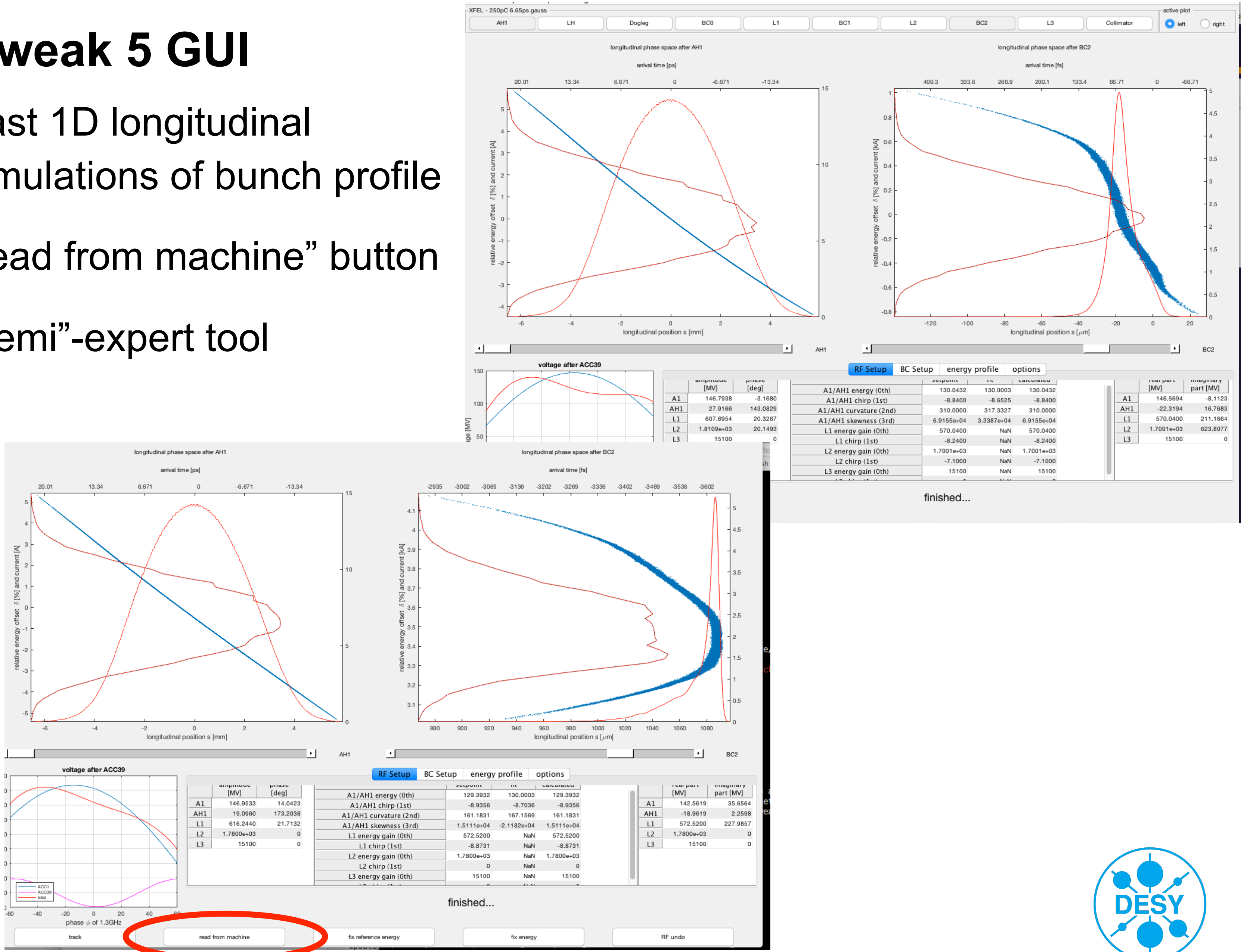


"Online" Simulations



RFTweak 5 GUI

- Fast 1D longitudinal simulations of bunch profile
- “read from machine” button
- “semi”-expert tool

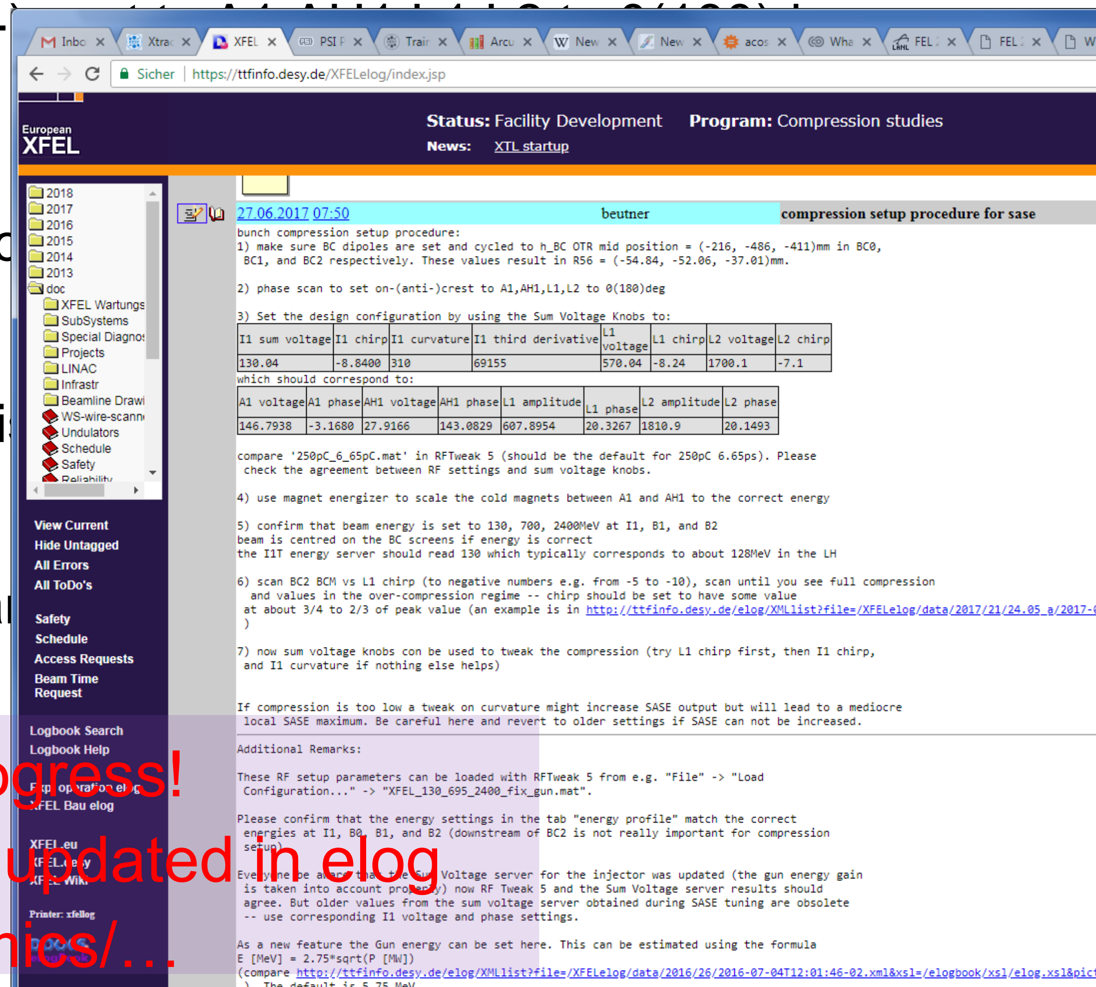


BCM


XFEL SASE1 Tuning Panel
Beam allowed / Shutter
Beam OFF
Bunch frequency
1.13 MHz
Num of bunches
Laser Heater
Running?
0.500 nC
SASE Gain @ XGM.2643.T9
XGM ok?
1 bunches
1212.5 µJ
10 %
@ 9.20keV
1.35 Å
SASE Viewer
XGMD Overview
Wavelength Controls
Wavelength:
nm
eV
Status: Ready
Undulator Controls
Set
All Stop
All to max. gap
All active to park
Longitudinal FB Loops
FB on/off
Toroid TORA 25.I1
BC0 BCM.2
Chirp I1
BC1 BCM.1
A2 Phase
BC2 BCM.1
Charge/BCMs History
I1 BAM
Gun Phase
BC0 BAM
BC2 BAM
Sumvoltage L2
BAMs History
Longitudinal Expert
Orbit FB Loops
INJ Orbit
L1 Orbit
L2 Orbit
L3 Orbit
SA1 Orbit
SA3 Orbit
Details
IBFB Details
Final Energies
LLRF Energy Gain
Beam Energy Meas.
I1/LH
L1/B1
L2/B2
L3/CL
T4
T4D
124.3 MeV
660.8 MeV
2415.6 MeV
11924.6 MeV
126.3 MeV
703.4 MeV
2403.0 MeV
13848.4 MeV
14105.3 MeV
14030.6 MeV
RF Control
GUN RF
RF sum I1
RF sum L1
RF sum L2
Final Energy L3
Voltage
Phase
Sum Voltage
Chirp
Curvature
Third Derivative
Sum Voltage Control
SASE1 Undulator Launch
CFX.2133.T2
CFX.2162.T2
CFY.2146.T2
CFY.2177.T2
mrad
2017-12-05 07:07:40

Compression Setup Procedure

- BC dipoles are set and cycled to h_BC OTR mid position = (-216, -486, -411)mm in BC0, BC1, and BC2 respectively.
- phase scan to set on-(anti-)
- Set design RF parameters
- use magnet energizer to sc
  AH1 to the correct energy
- confirm that beam energy i
  and B2
- now sum voltage knobs ca
  L1 chirp first, then I1 chirp,



27.06.2017 07:50 beutner compression setup procedure for sase

bunch compression setup procedure:
1) make sure BC dipoles are set and cycled to h_BC OTR mid position = (-216, -486, -411)mm in BC0, BC1, and BC2 respectively. These values result in R56 = (-54.84, -52.06, -37.01)mm.

2) phase scan to set on-(anti-)crest to A1,AH1,L1,L2 to 0(180)deg

3) Set the design configuration by using the Sum Voltage Knobs to:

I1 sum voltage	I1 chirp	I1 curvature	I1 third derivative	L1 voltage	L1 chirp	L2 voltage	L2 chirp
130.04	-8.8400	310	69155	570.04	-8.24	1700.1	-7.1

which should correspond to:

A1 voltage	A1 phase	AH1 voltage	AH1 phase	L1 amplitude	L1 phase	L2 amplitude	L2 phase
146.7938	-3.1680	27.9166	143.0829	607.8954	20.3267	1810.9	20.1493

compare '250pC_6_65pC.mat' in RFTweak 5 (should be the default for 250pC 6.65ps). Please check the agreement between RF settings and sum voltage knobs.

4) use magnet energizer to scale the cold magnets between A1 and AH1 to the correct energy

5) confirm that beam energy is set to 130, 700, 2400MeV at I1, B1, and B2
beam is centred on the BC screens if energy is correct
the I1T energy server should read 130 which typically corresponds to about 128MeV in the LH

6) scan BC2 BCM vs L1 chirp (to negative numbers e.g. from -5 to -10), scan until you see full compression and values in the over-compression regime -- chirp should be set to have some value at about 3/4 to 2/3 of peak value (an example is in http://ttfinfo.desy.de/elog/XMLlist?file=/XFELelog/data/2017/21/24.05_a/2017-
)

7) now sum voltage knobs con be used to tweak the compression (try L1 chirp first, then I1 chirp, and I1 curvature if nothing else helps)

If compression is too low a tweak on curvature might increase SASE output but will lead to a mediocre local SASE maximum. Be careful here and revert to older settings if SASE can not be increased.

Additional Remarks:

These RF setup parameters can be loaded with RFTweak 5 from e.g. "File" -> "Load Configuration..." -> "XFEL_130_695_2400_fix_gun.mat".

Please confirm that the energy settings in the tab "energy profile" match the correct energies at I1, B0, B1, and B2 (downstream of BC2 is not really important for compression setup)

Everyone be aware that the Sum Voltage server for the injector was updated (the gun energy gain is taken into account properly) now RF Tweak 5 and the Sum Voltage server results should agree. But older values from the sum voltage server obtained during SASE tuning are obsolete -- use corresponding I1 voltage and phase settings.

As a new feature the Gun energy can be set here. This can be estimated using the formula
E [MeV] = 2.75*sqrt(P [MW])
(compare http://ttfinfo.desy.de/elog/XMLlist?file=/XFELelog/data/2016/26/2016-07-04T12:01:46-02.xml&xsl=/elogbook/xsl/elog.xsl&pic

This is work in progress!
Procedure will be updated in elog
/doc/Beam Dynamics/…

European XFEL

Thank You for Your Attention!

Questions?

Literature:

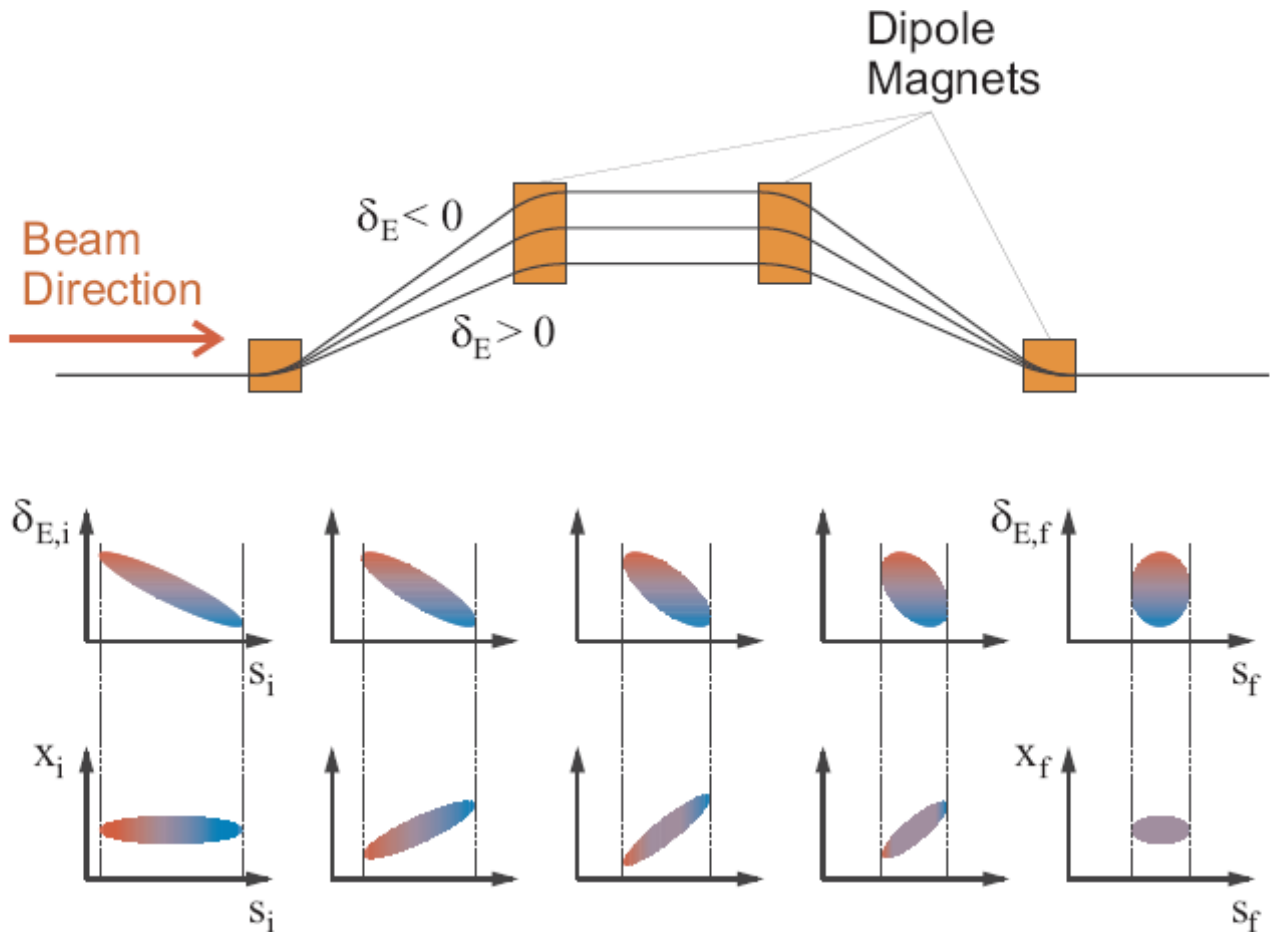
- Igor Zagorodnov and Martin Dohlus, “Semianalytical modeling of multistage bunch compression with collective effects”
  Phys. Rev. ST Accel. Beams 14, 014403 – Published 13 January 2011

- 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), …

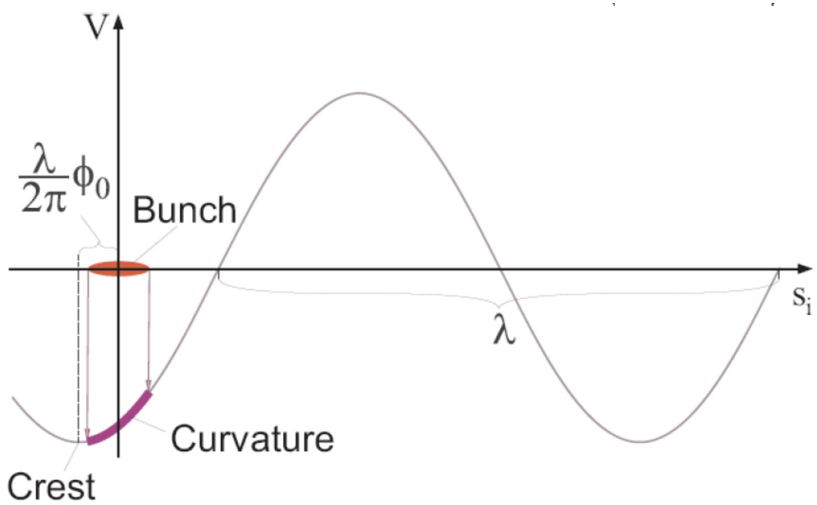
In-house Experts: Martin Dohlus, Igor Zagorodnov, Torsten Limberg, BB

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



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

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

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

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

$$\approx As + Bs^2$$

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

Linear Compression

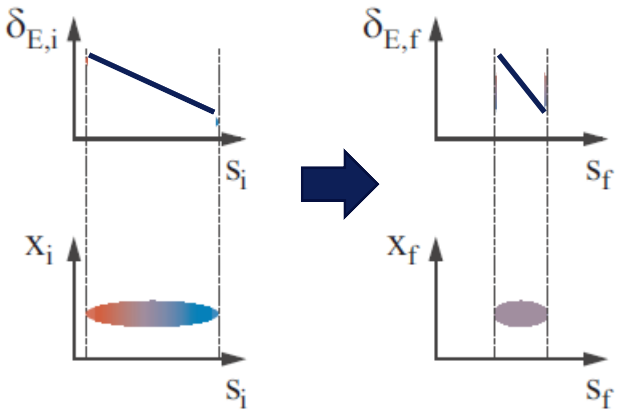
$$\delta(s_{\text{initial}}) = A s_{\text{initial}}$$

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

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

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

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



Linear Compression with Uncorrelated Energy Spread

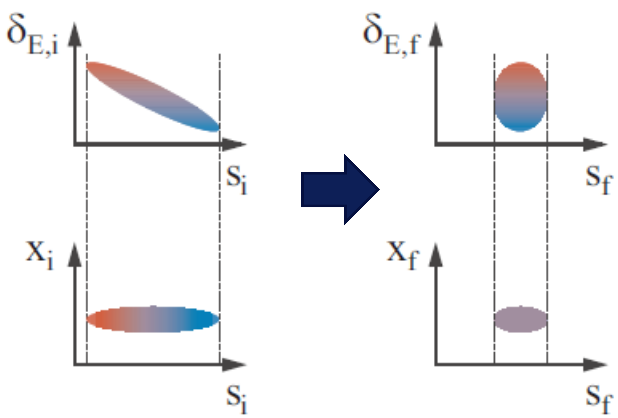
each particle *i* has an individual “random” energy offset

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

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

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

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



$$\text{if} \;\; (1 + AR_{56}) = 0$$

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

Typically the “full” compression is avoided…

European XFEL

DESY

Simple Compression Setup

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

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

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

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

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

Is this Ok?

Non-linear Compression

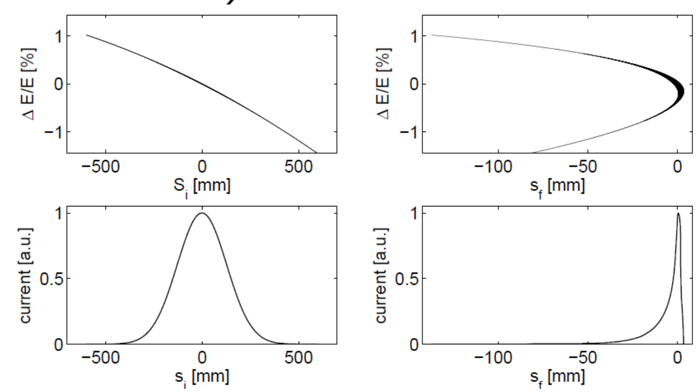
total energy E

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

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

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

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

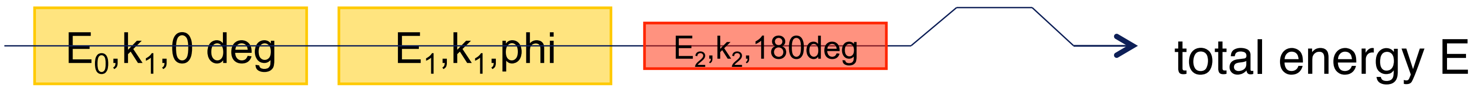


Can we tune the T_{566}-term to compensate the E_1 quadratic-term?

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

This is NOT Ok!

Linarised Compression



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

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

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

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

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

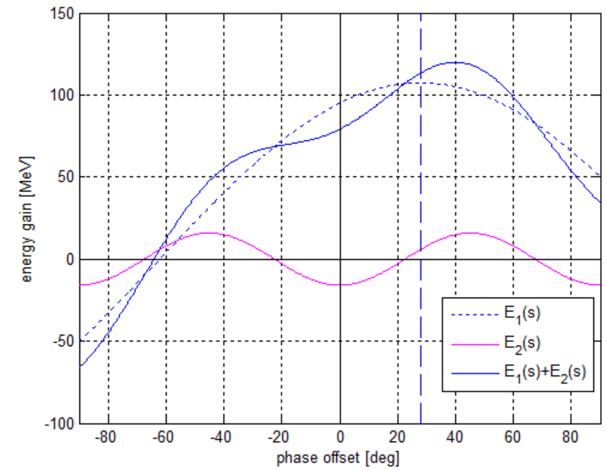
Energy Compensation

total energy E

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

$$E_1 \sin(\varphi) = E_1' \sin(\varphi')$$

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

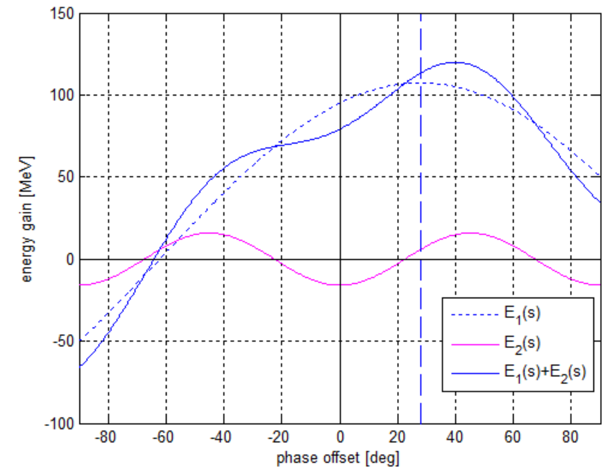


Compensation of energy loss is required while the slope must be maintained.

Energy Compensation

total energy E

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



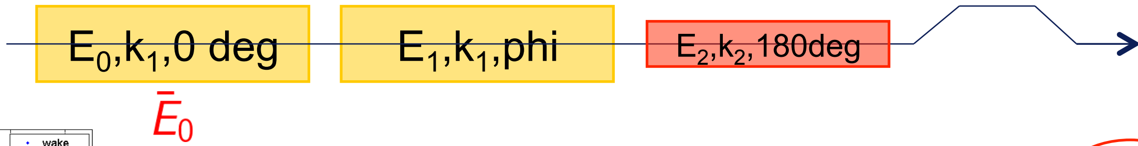
$$E_1 \sin(\varphi) = E_1' \sin(\varphi')$$
$$E_1 \cos(\varphi) + E_2 = E_1' \cos(\varphi')$$

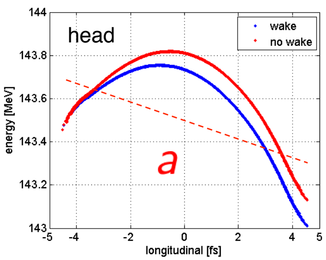
$$\Rightarrow \quad \varphi' = \arctan\left(\frac{E_1 \sin(\varphi)}{E_1 \cos(\varphi) + E_2} \right)$$

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

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