



Bunch Compression Operation at the European XFEL

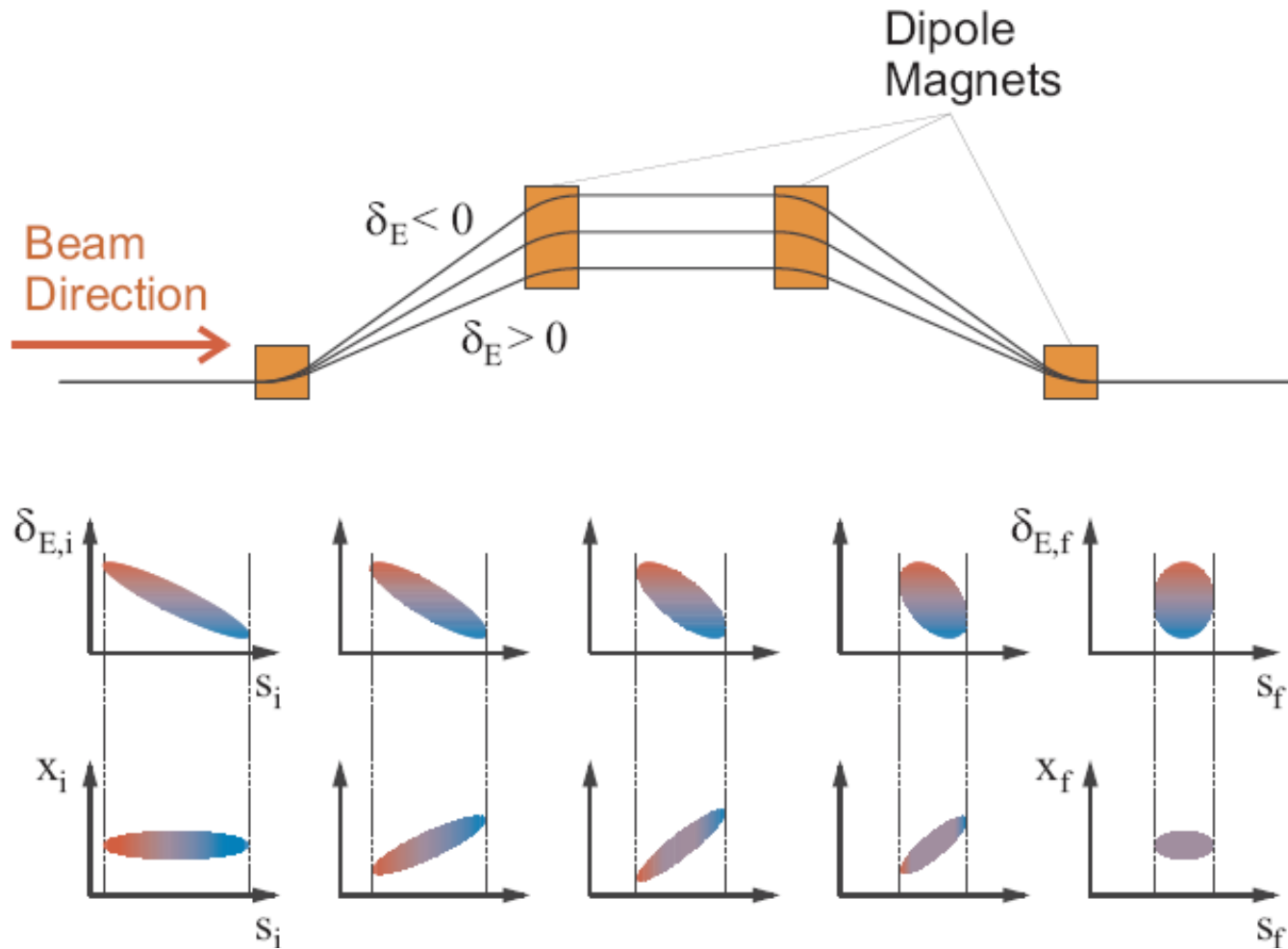
Bolko Beutner

Operator Training
February 2018

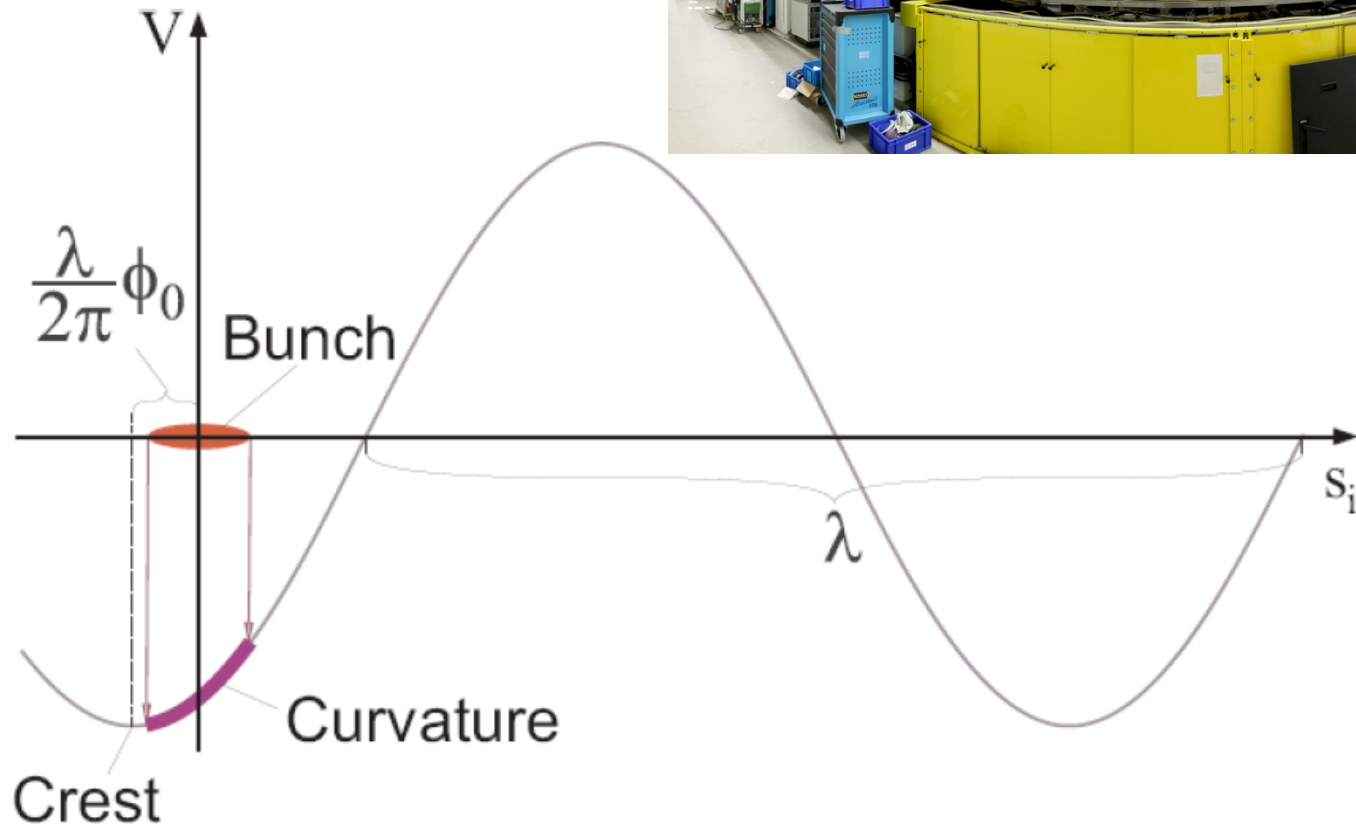
FEL Performance

- 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

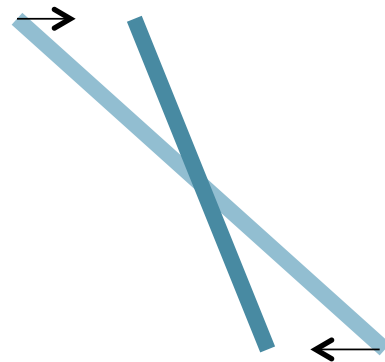


Energy Chirp Generation

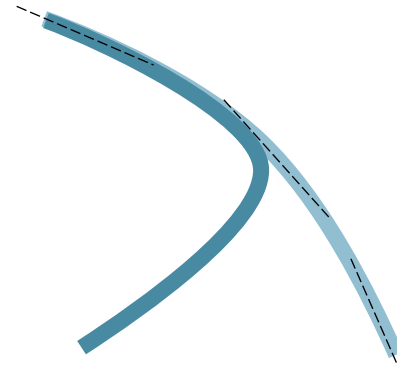


“Non-linear” Compression

Linear Compression:

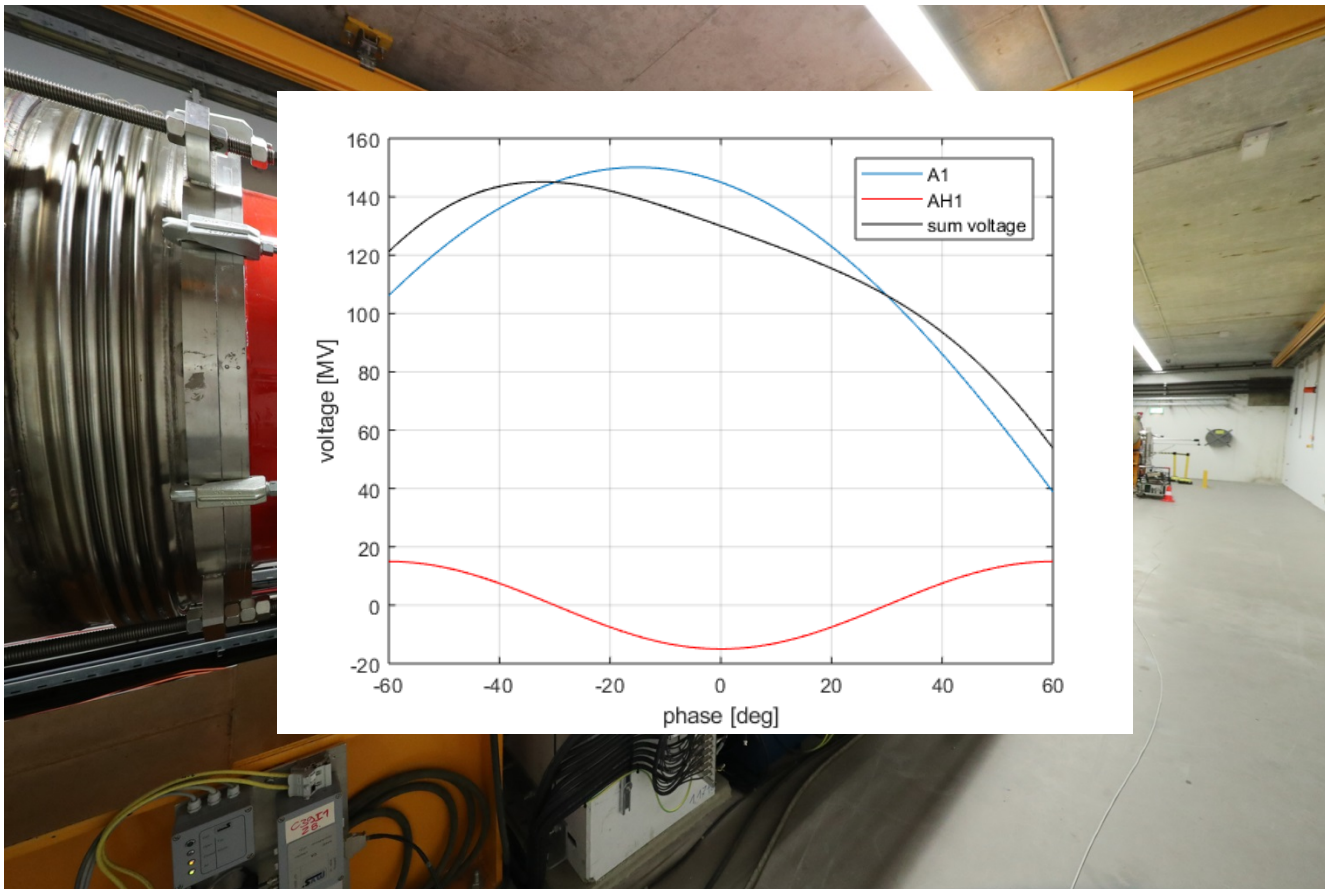


Non-Linear Compression:



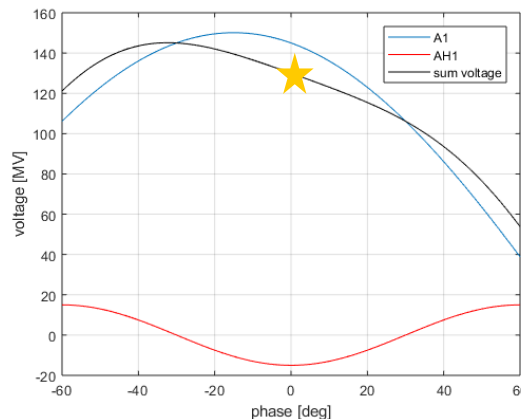
Phase Space Linearisation

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



Sum Voltage

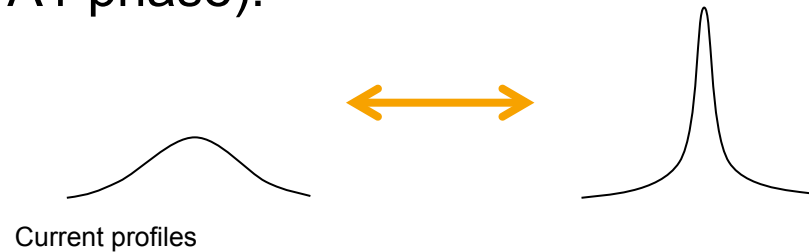
- Setup of RF phase and voltages to get a certain energy chirp is cumbersome
- RF parameters can be directly calculated from the Taylor coefficients (energy, chirp, curvature) at the beam position



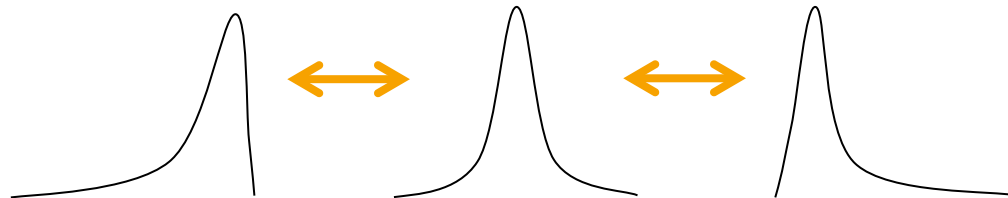
- Tuning one of the Taylor coefficients do not change the others, especially the beam energy is not changed (provided that the on-crest phases are correct)

Sum Voltage Effects

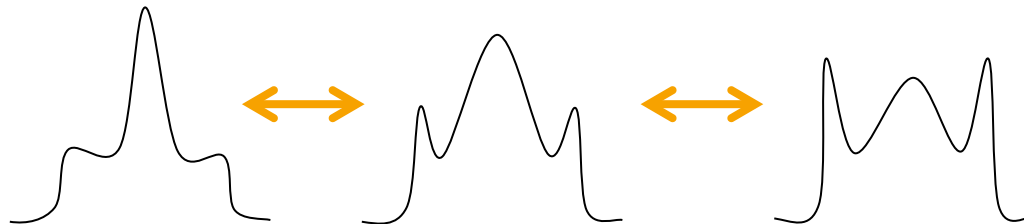
■ Chirp (mostly A1 phase):



■ Curvature (mostly AH1 voltage):



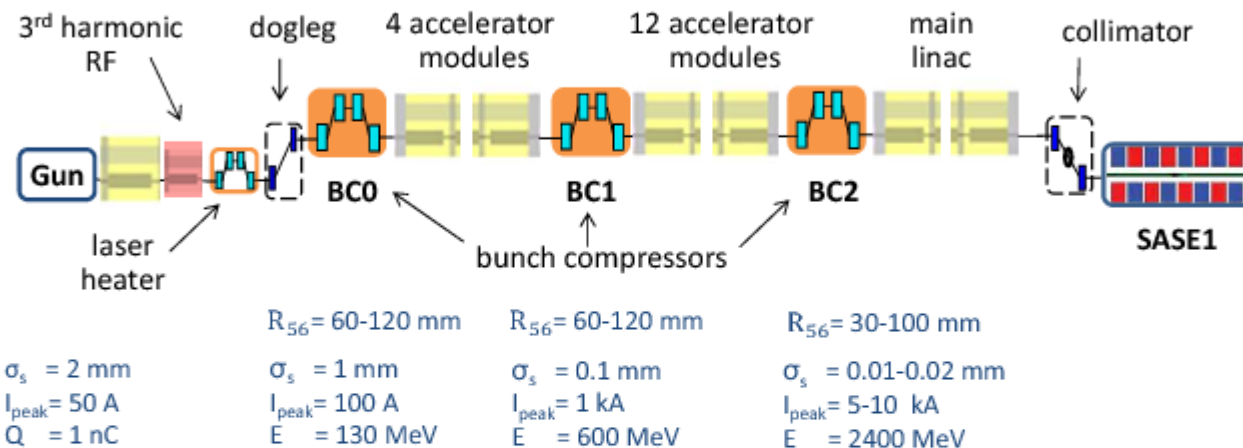
■ Third Order “Skewness” (AH1 voltage and phase):



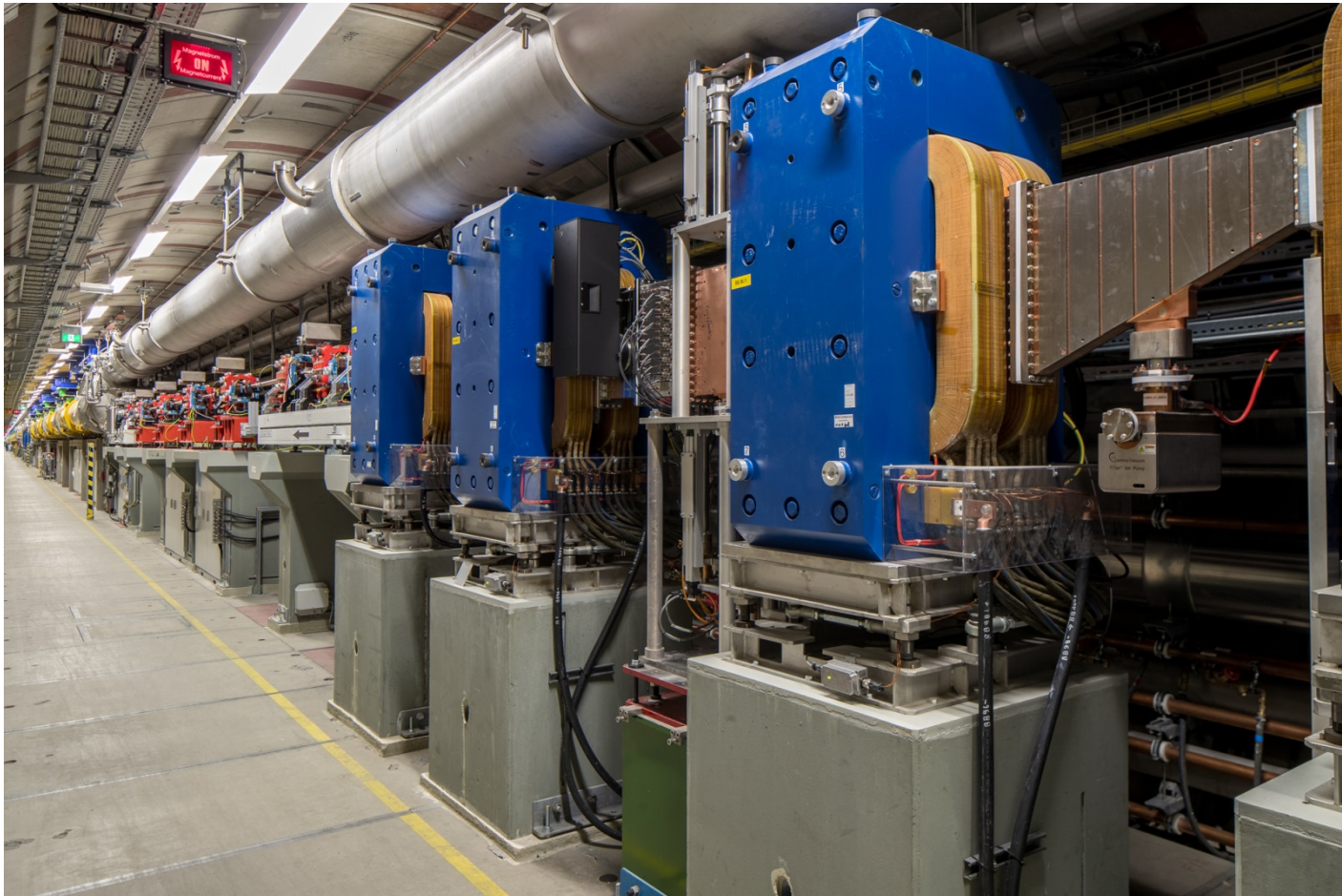
Multi-Stage Compression

- 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

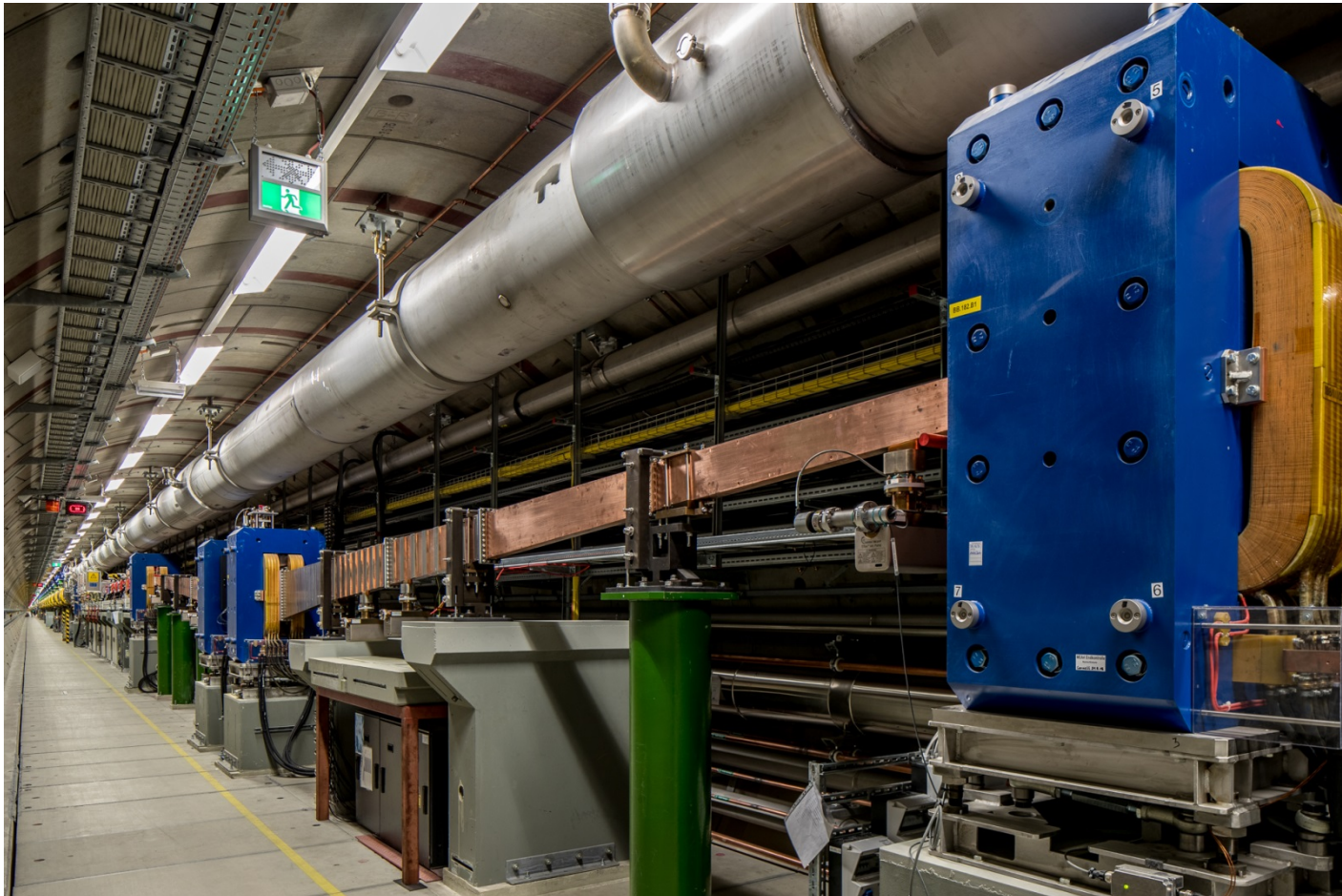
=> Multi-stage compression



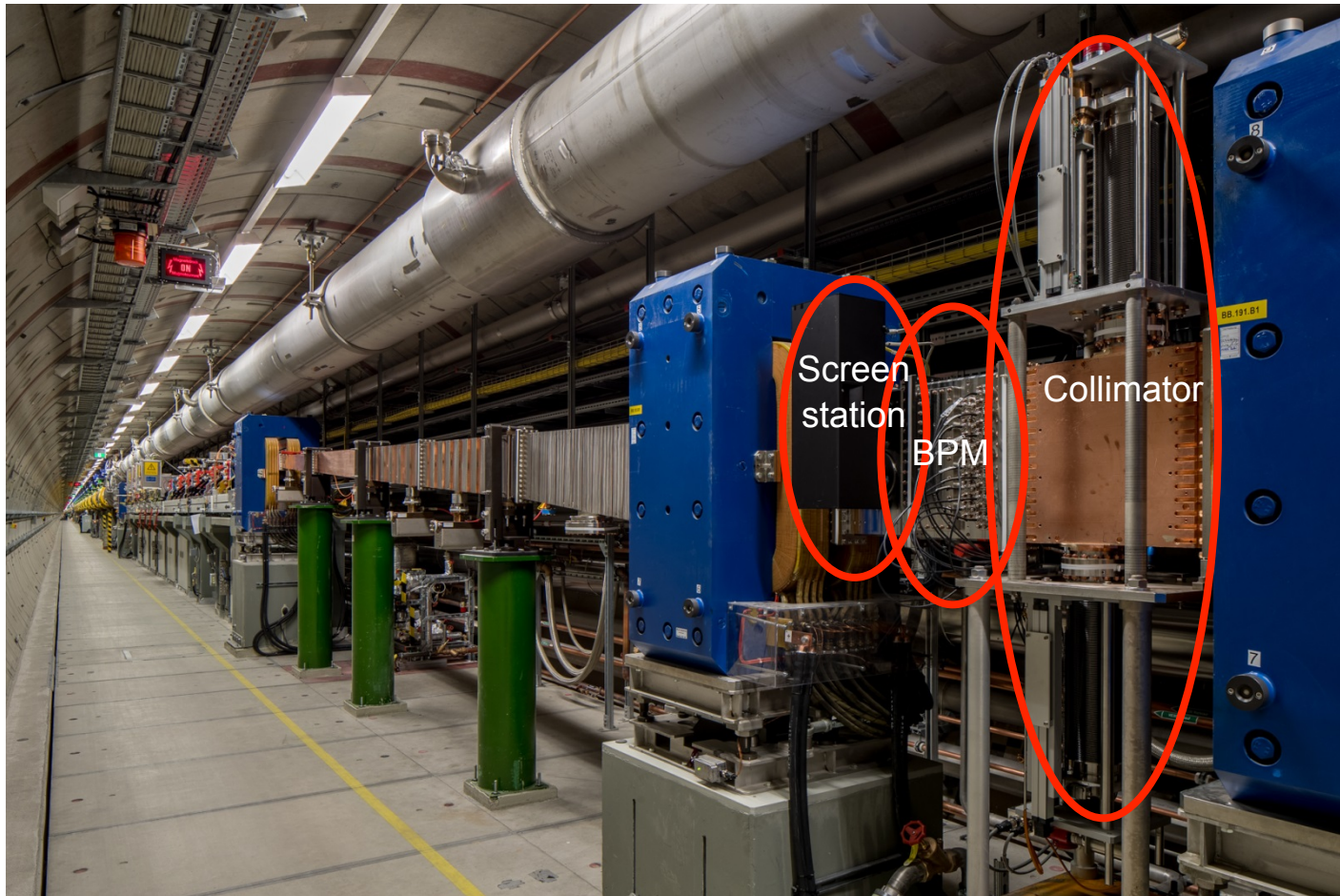
BC0



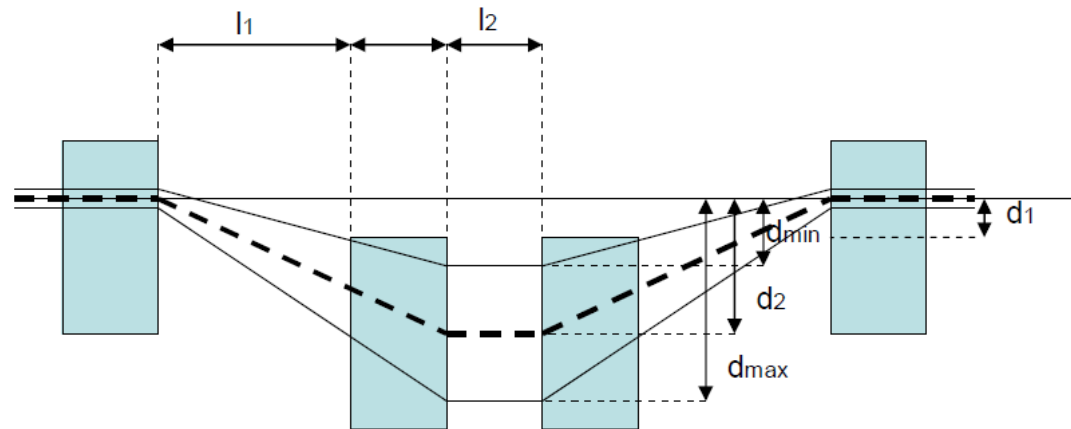
BC1



BC1

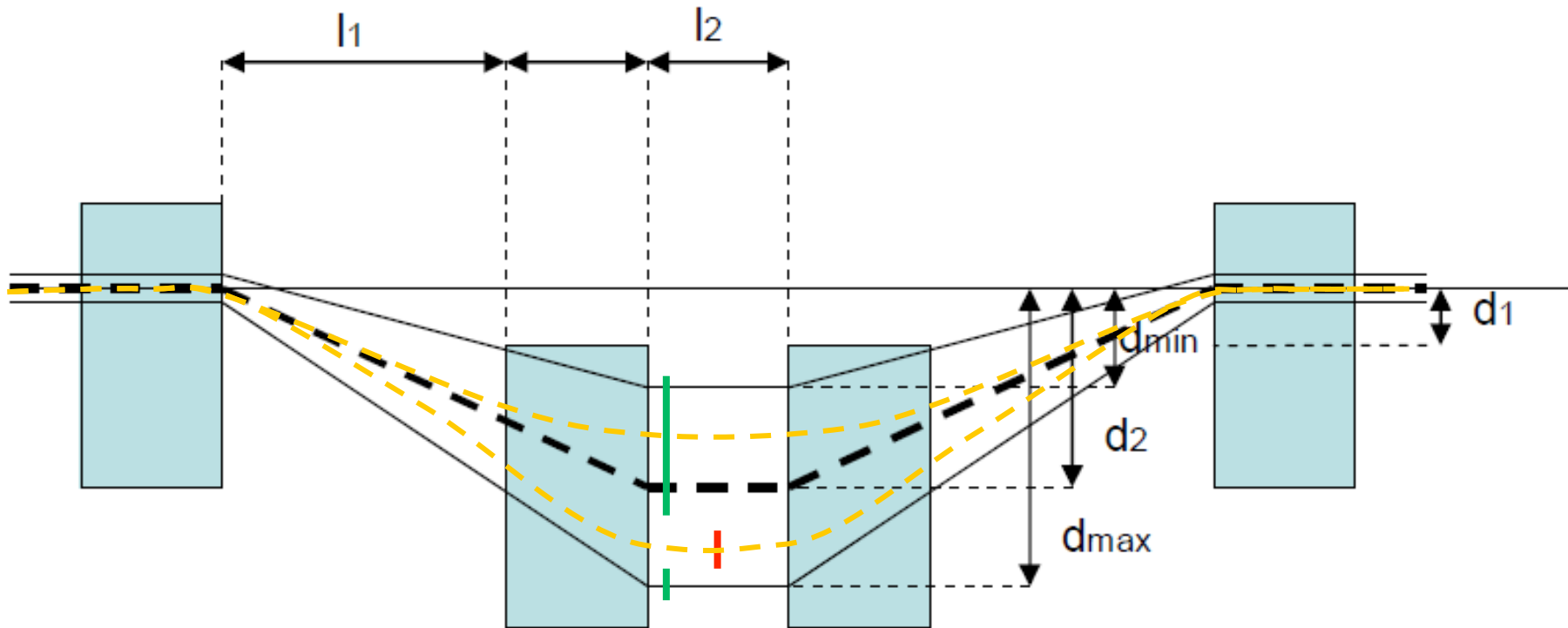


XFEL BC Overview



	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!

The screenshot displays the XFEL control interface for the SUBTRAIN - ALL system. At the top, the XFEL logo is visible on the left, and the title 'SUBTRAIN - ALL' is centered. Below the title bar, there are several control elements: a 'Beam ON/OFF' toggle (checked), a 'Bunches' counter showing 0, and a '101 %' status indicator. The main area of the interface is a detailed beamline diagram. It shows a sequence of components including undulators (represented by blue rectangles with wavy lines), wigglers (represented by blue rectangles with a single wavy line), and various diagnostic or control points (represented by circles with text like 'PC', 'W1', 'W2', 'W3', 'W4', 'W5', 'W6', 'W7', 'W8', 'W9', 'W10', 'W11', 'W12', 'W13', 'W14', 'W15', 'W16', 'W17', 'W18', 'W19', 'W20', 'W21', 'W22', 'W23', 'W24', 'W25', 'W26', 'W27', 'W28', 'W29', 'W30', 'W31', 'W32', 'W33', 'W34', 'W35', 'W36', 'W37', 'W38', 'W39', 'W40', 'W41', 'W42', 'W43', 'W44', 'W45', 'W46', 'W47', 'W48', 'W49', 'W50', 'W51', 'W52', 'W53', 'W54', 'W55', 'W56', 'W57', 'W58', 'W59', 'W60', 'W61', 'W62', 'W63', 'W64', 'W65', 'W66', 'W67', 'W68', 'W69', 'W70', 'W71', 'W72', 'W73', 'W74', 'W75', 'W76', 'W77', 'W78', 'W79', 'W80', 'W81', 'W82', 'W83', 'W84', 'W85', 'W86', 'W87', 'W88', 'W89', 'W90', 'W91', 'W92', 'W93', 'W94', 'W95', 'W96', 'W97', 'W98', 'W99', 'W100'). A red circle highlights a specific component in the beamline. The bottom status bar shows '175 m' and 'XFEL Overview'.

The image displays two side-by-side screenshots of the 'Motor Expert Panel' software interface, which is used for controlling motors in a laboratory setting. The interface is divided into several sections: a top header with the motor name and location, a central control area with input fields for facility, device, and location, and a bottom status section with checkboxes for various motor states.

Left Screenshot (COLU.192.B1):

- Header:** Motor Expert Panel, None
- Facility/Device/Location:** XFEL.DIAG, COLL.MOVER, COLU.192.B1
- Status:** ok
- Control Area:**
 - IST: 60000000
 - SOLL: 60000000 (with a green 'H' button next to it)
 - Wegmessung: 18836
 - Buttons: Start (green), Stopp (red), Reset, Auf 0 setzen
- Status Section:**
 - Motor fährt/Haltestrom
 - Motor freigegeben
 - Bereit für neue Verfahrbewegung (checked)
 - Fehler: 0
 - Positiven Endschalter erreicht
 - Negativen Endschalter erreicht
 - Virtuelles Limit erreicht

Right Screenshot (COLO.192.B1):

- Header:** Motor Expert Panel, None
- Facility/Device/Location:** XFEL.DIAG, COLL.MOVER, COLO.192.B1
- Status:** ok
- Control Area:**
 - IST: 93110000
 - SOLL: 93110000 (with a green 'H' button next to it)
 - Wegmessung: 12739
 - Buttons: Start (green), Stopp (red), Reset, Auf 0 setzen
- Status Section:**
 - Motor fährt/Haltestrom
 - Motor freigegeben
 - Bereit für neue Verfahrbewegung (checked)
 - Fehler: 0
 - Positiven Endschalter erreicht
 - Negativen Endschalter erreicht
 - Virtuelles Limit erreicht

Below the screenshots, there is a list of instructions for the experiment:

- 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

/svn/global/Magnet/Chicane/ChicaneControlMain.xml XFEL.MAGNETS/CHICANE//

XFEL Chicane Server

LH

Energy 130.00 MeV ☒

Angle $\hat{\sim}5.70$ deg ☒

Design: 5.7000

R_{56} $\hat{\sim}4.34$ mm ☒

h_{BC} $\hat{\sim}29.9$ mm ☒

dt 7.19 ps ☒

Gen. field $\hat{\sim}0.1741$ T ☒

Power supply circuit

Class Dipole

PS Circuit BL.1.I1

☒ PS On/Off

☐ Circuit write protection

☒ Switched on

☒ No fault ☒ Idle ☒

Magnet 1: BL.48I.I1

Magnet 2: BL.48II.I1

Magnet 3: BL.50I.I1

Magnet 4: BL.50II.I1

BC0

Energy 130.00 MeV ☒

Angle $\hat{\sim}8.19$ deg ☒

Design: -6.8509

R_{56} $\hat{\sim}54.80$ mm ☒

h_{BC} $\hat{\sim}215.5$ mm ☒

dt 90.16 ps ☒

Gen. field ~~100.0000~~ T ☒

Power supply circuit

Class Dipole

PS Circuit BB.1.I1

☒ PS On/Off

☐ Circuit write protection

☒ Switched on

☒ No fault ☒ Idle ☒

Magnet 1: BB.96.I1

Magnet 2: BB.98.I1

Magnet 3: BB.100.I1

Magnet 4: BB.101.I1

BC1

Energy 700.00 MeV ☒

Angle $\hat{\sim}3.09$ deg ☒

Design: -2.8628

R_{56} $\hat{\sim}51.44$ mm ☒

h_{BC} $\hat{\sim}485.8$ mm ☒

dt 85.61 ps ☒

Gen. field $\hat{\sim}0.2255$ T ☒

Power supply circuit

Class Dipole

PS Circuit BB.1.B1

☒ PS On/Off

☐ Circuit write protection

☒ Switched on

☒ No fault ☒ Idle ☒

Magnet 1: BB.182.B1

Magnet 2: BB.191.B1

Magnet 3: BB.193.B1

Magnet 4: BB.202.B1

BC2

Energy 2418.74 MeV ☒

Angle $\hat{\sim}2.61$ deg ☒

Design: -2.3857

R_{56} $\hat{\sim}36.67$ mm ☒

h_{BC} $\hat{\sim}410.2$ mm ☒

dt 61.06 ps ☒

Gen. field $\hat{\sim}0.6582$ T ☒

Power supply circuit

Class Dipole

PS Circuit BB.1.B2

☒ PS On/Off

☐ Circuit write protection

☒ Switched on

☒ No fault ☒ Idle ☒

Magnet 1: BB.393.B2

Magnet 2: BB.402.B2

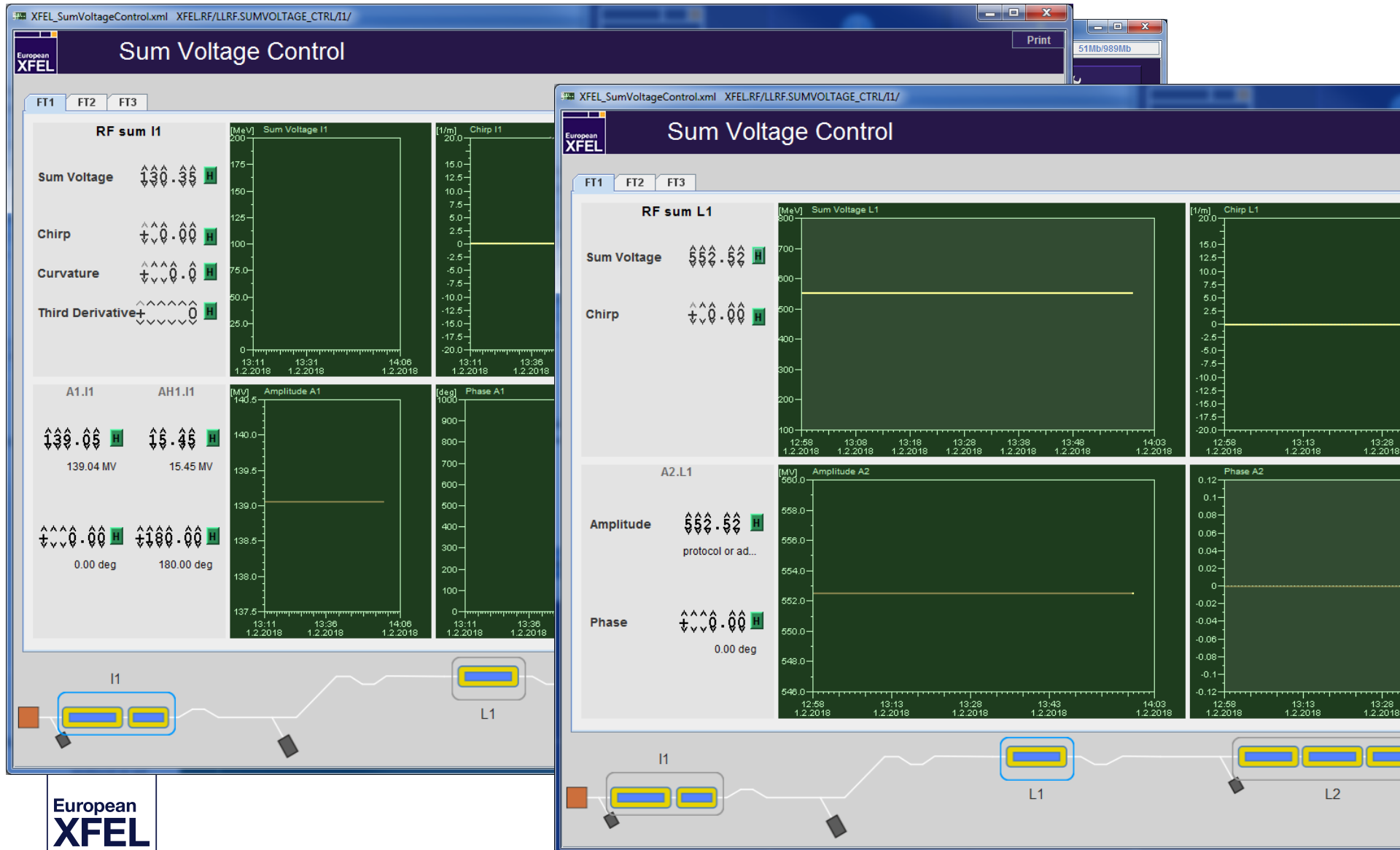
Magnet 3: BB.404.B2

Magnet 4: BB.413.B2

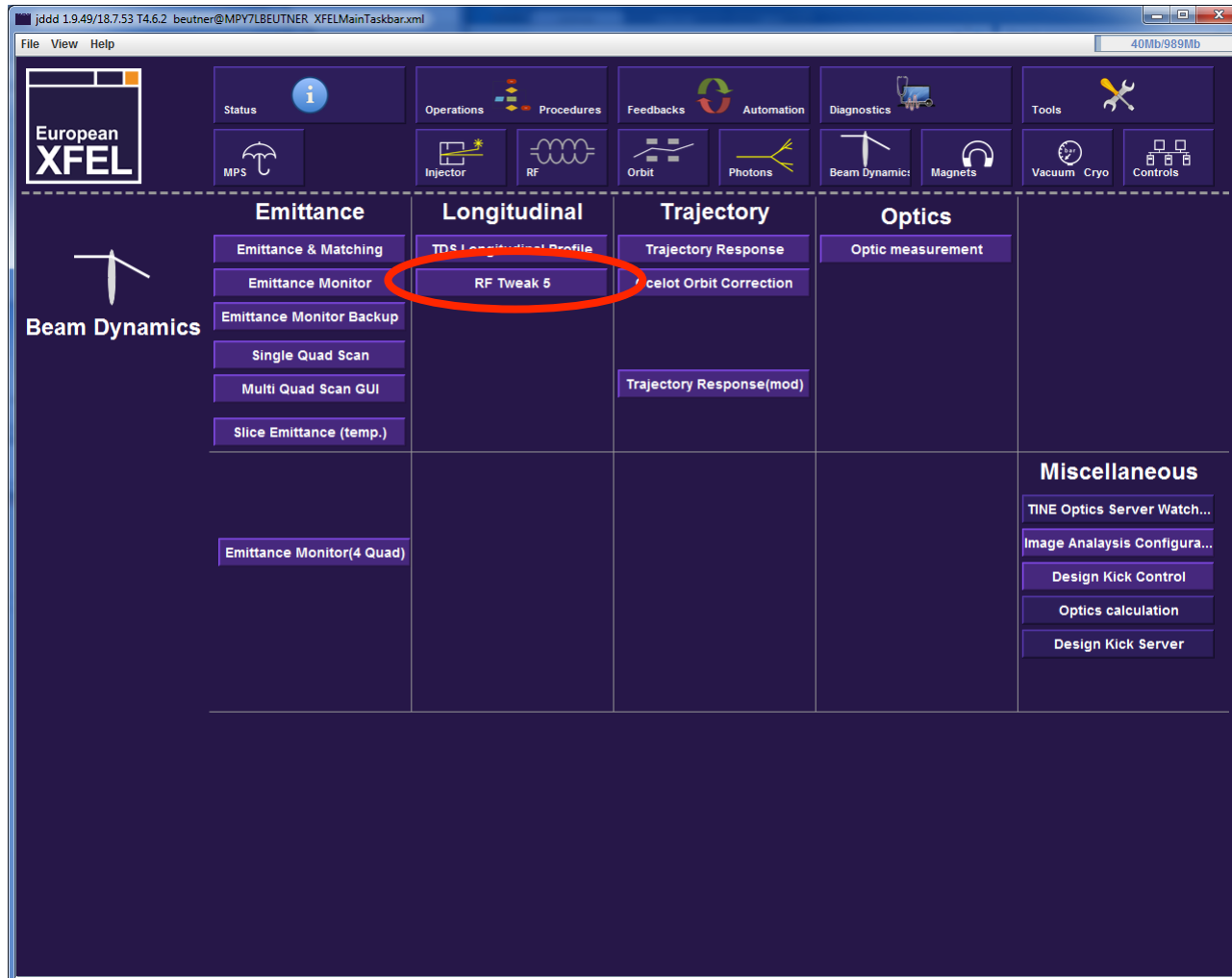
Static values

B0	B1	B2
h_{BC} according to longlist -180 mm	h_{BC} according to longlist -450 mm	h_{BC} according to longlist -375 mm
h_{BC} OTR mid position -216 mm	h_{BC} OTR mid position -486 mm	h_{BC} OTR mid position -411 mm

RF Setup and Tuning

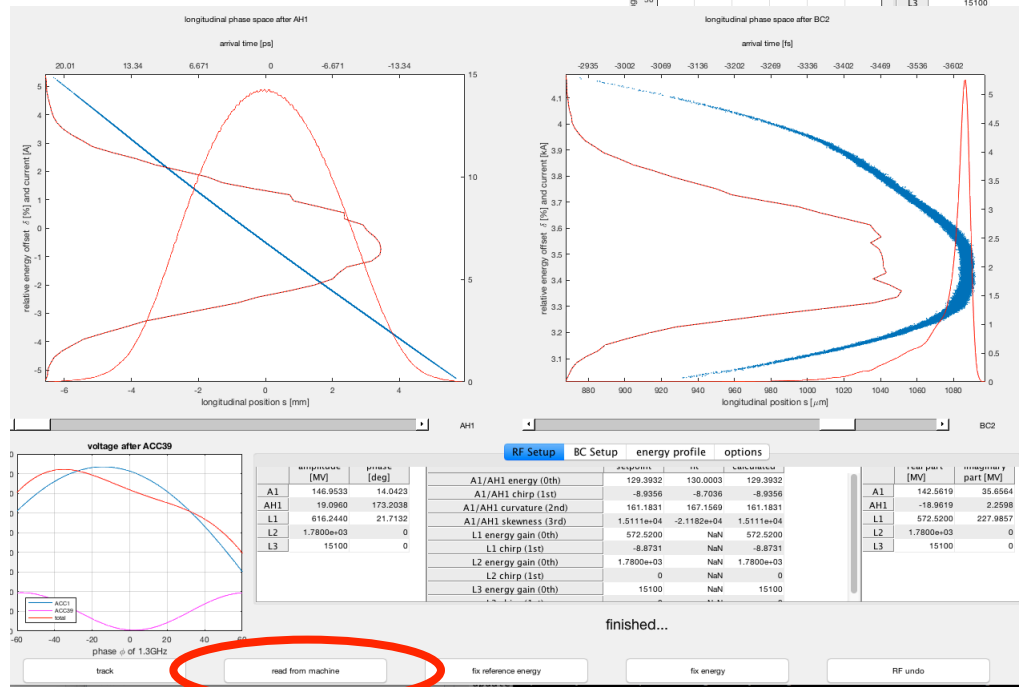
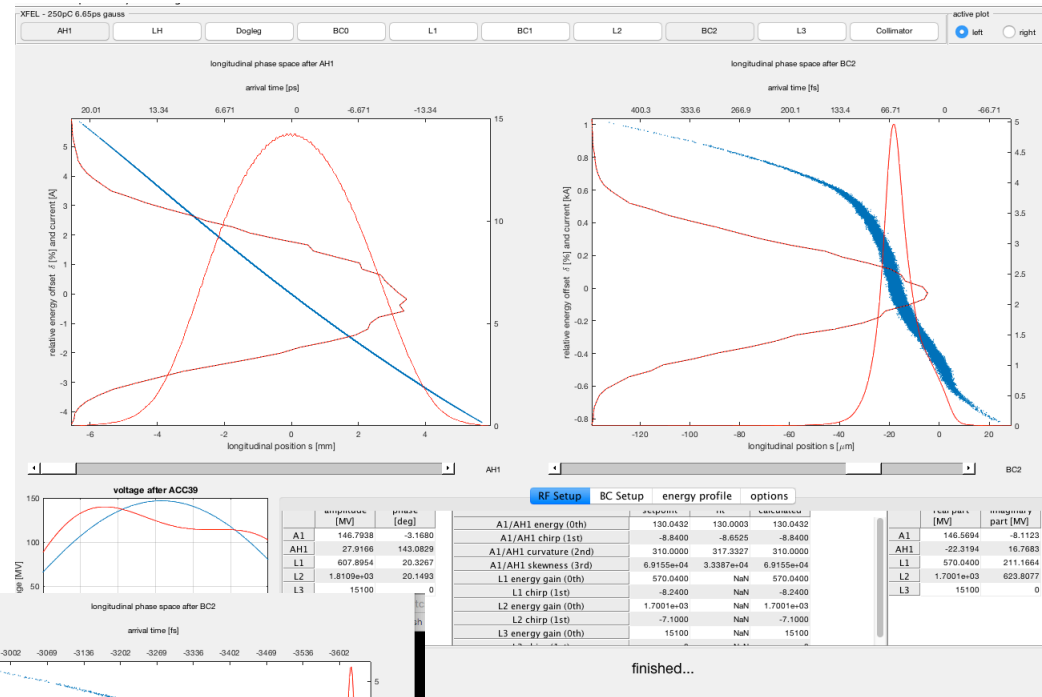


“Online” Simulations



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: 1

Laser Heater: ☒ 0.500 nC

Running?: ☒

SASE Gain @ XGM.2643.T9: 1 bunches

1212.5 μ J 10 % @ 9.20keV 1.35 Å

Wavelength Controls: Wavelength: 0.13 nm, 9200.00 eV

Status: Ready

Longitudinal FB Loops: ☒ FB on/off

Longitudinal Expert

Orbit FB Loops: INJ Orbit, L1 Orbit, L2 Orbit, L3 Orbit, SA1 Orbit, SA3 Orbit

Final Energies:

	I1/LH	L1/B1	L2/B2	L3/CL	T4	T4D
LLRF Energy Gain	124.3 MeV	660.8 MeV	2415.6 MeV	11924.6 MeV	14105.3 MeV	14030.6 MeV
Beam Energy Meas.	126.3 MeV	703.4 MeV	2403.0 MeV	13848.4 MeV		

RF Control:

	GUN RF	RF sum I1	RF sum L1	RF sum L2	Final Energy L3
Voltage	53.00 H	Sum Voltage 124.50 H	Sum Voltage 536.63 H	Sum Voltage 1755.80 H	14100.00 H
Phase	-42.50 H	Chirp -7.37 H	Chirp -12.29 H	Chirp -0.21 H	
		Curvature 170.0 H			
		Third Derivative -1000 H			

SASE1 Undulator Launch:

	CFX.2133.T2	CFX.2162.T2	CFY.2146.T2	CFY.2177.T2
	+0.0600 mrad	+0.0357 mrad	+0.0144 mrad	-0.0051 mrad

Sum Voltage Control

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-)crest
- Set design RF parameters
- use magnet energizer to scale AH1 to the correct energy
- confirm that beam energy is set to 130, 700, 2400 MeV at I1, B1, and B2
- now sum voltage knobs can be used to tweak the compression (try L1 chirp first, then I1 chirp, and I1 curvature if nothing else helps)

Status: Facility Development **Program:** Compression studies
News: [XTL_startup](#)

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, 2400 MeV at I1, B1, and B2
- 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/XMList?file=XFELeLog/data/2017/21/24.05_a/2017-05-24_12.01.46-02.xml&xsl=/eLogbook/xsl/eLogbook.xsl)
- 7) now sum voltage knobs can 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).

Every time the beamline 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 $E \text{ [MeV]} = 2.75 \sqrt{\text{sort}(P \text{ [MW]})}$ (compare <http://ttfinfo.desy.de/eLog/XMList?file=XFELeLog/data/2016/26/2016-07-04T12:01:46-02.xml&xsl=/eLogbook/xsl/eLogbook.xsl>)

This is work in progress!

Procedure will be updated in eLog

/doc/Beam Dynamics/...

Thank You for Your Attention!

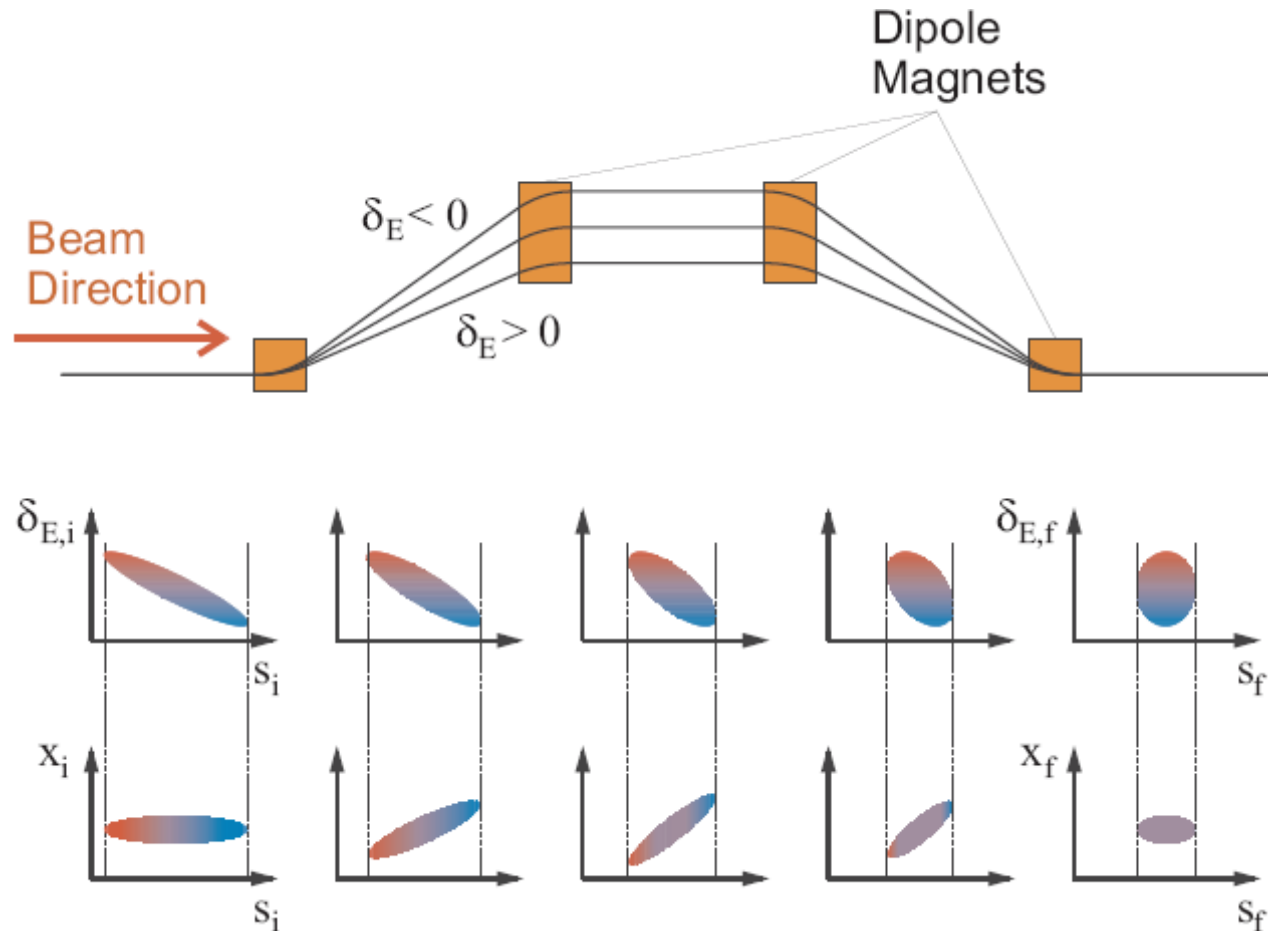
Questions?

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>), ...

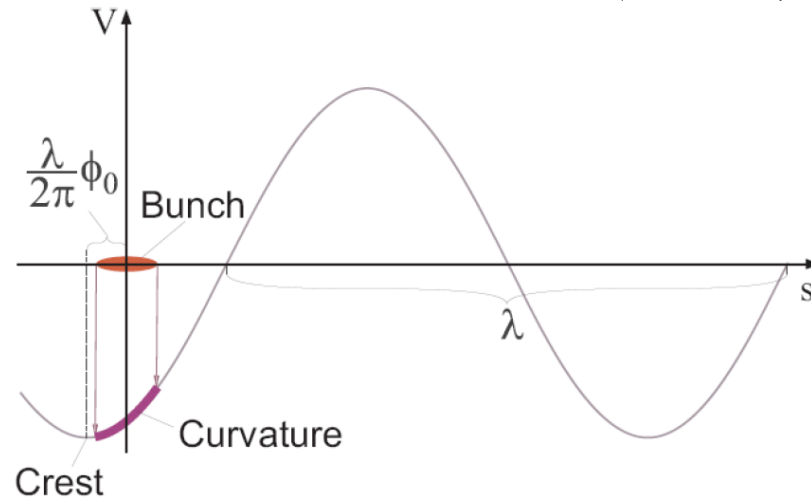
In-house Experts: Martin Dohlus, Igor Zagorodnov, Torsten Limberg, BB

Bunch Compression – with Formulas



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

Energy Chirp Generation



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

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

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

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

$$\approx As + Bs^2$$

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

Linear Compression

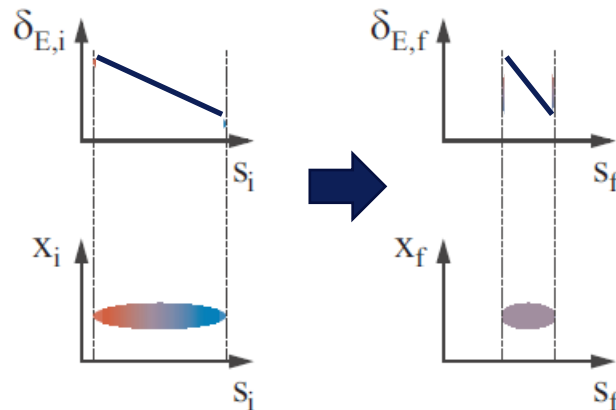
$$\delta(s_{\text{initial}}) = A s_{\text{initial}}$$

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

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

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

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



Linear Compression with Uncorrelated Energy Spread

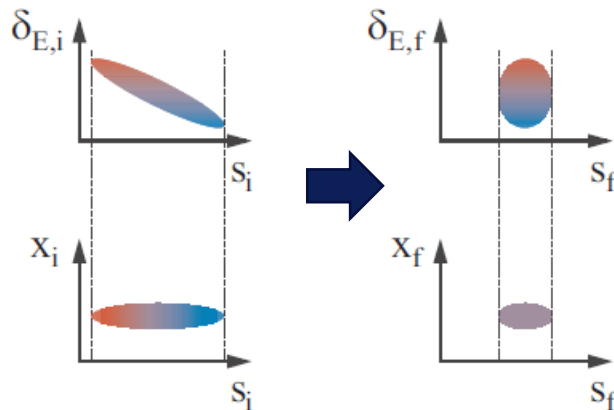
each particle i has an individual “random” energy offset

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

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

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

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



Typically the “full” compression is avoided...

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

$$\sigma_{s_{\text{final}}}^{\text{min}} \approx |R_{56}| \sigma_{\delta^i}$$

Simple Compression Setup



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

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

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

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

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

Is this Ok?

Non-linear Compression

$E_0, k_1, 0 \text{ deg}$

E_1, k_1, ϕ

total energy E

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

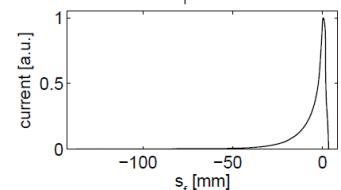
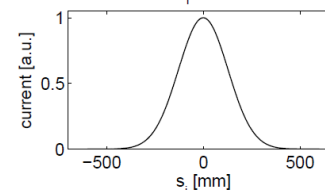
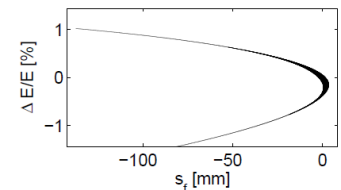
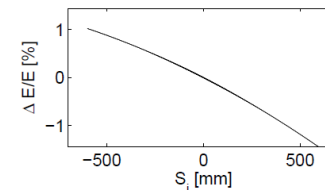
$$\delta = A s_{\text{initial}} + B s_{\text{initial}}^2 + \dots$$

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

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

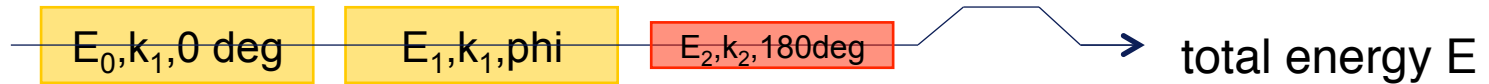
Can we tune the T_{566} -term to compensate the E_1 quadratic-term?

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



This is NOT Ok!

Linarised Compression



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

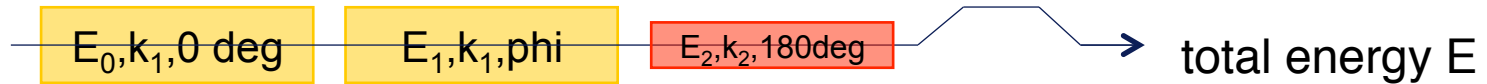
$$\delta = A s_{\text{initial}} + B s_{\text{initial}}^2 + \dots$$

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

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

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

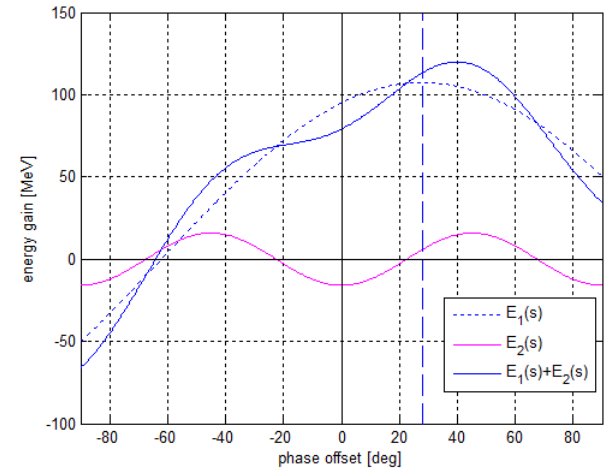
Energy Compensation



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

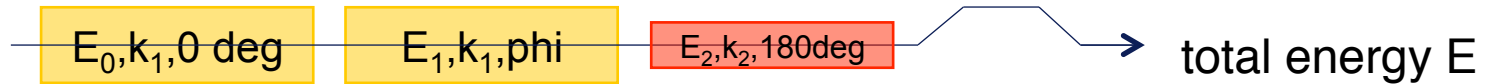
$$E_1 \sin(\varphi) = E'_1 \sin(\varphi')$$

$$E_1 \cos(\varphi) + E_2 = E'_1 \cos(\varphi')$$



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

Energy Compensation



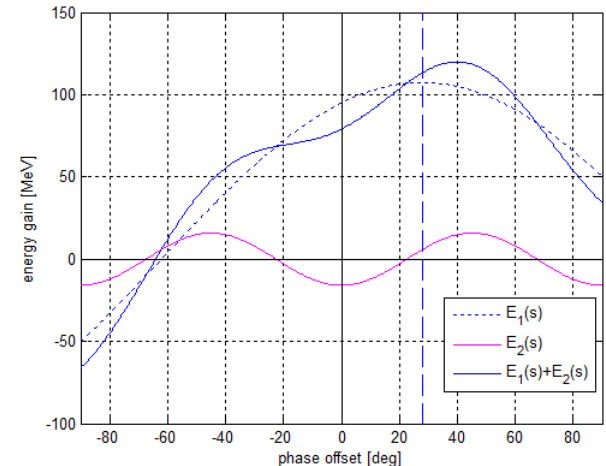
$$E_2 = \left(E_1 \cos(\varphi) + 3 \frac{E_1^2}{E} \sin^2(\varphi) \right) \frac{k_1^2}{k_2^2}$$

$$E_1 \sin(\varphi) = E'_1 \sin(\varphi')$$

$$E_1 \cos(\varphi) + E_2 = E'_1 \cos(\varphi')$$

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

$$E'_1 = E_1 \frac{\sin(\varphi)}{\sin(\varphi')}$$

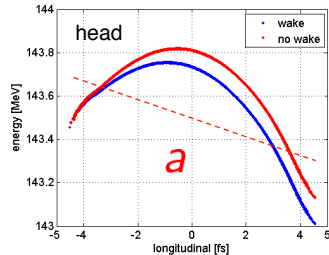


Compensation of energy loss is required while the slope must be maintained.

(Almost) General Solution for Single Stage BC

 $E_0, k_1, 0 \text{ deg}$
 E_1, k_1, phi
 $E_2, k_2, 180 \text{ deg}$

total energy E


 \bar{E}_0

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

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

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

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

$$E'_1 = E_1 \frac{\sin(\varphi)}{\sin(\varphi')}$$

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

The End