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Beam Quality for High Brightness Beam: Application of SwissFEL

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Outline

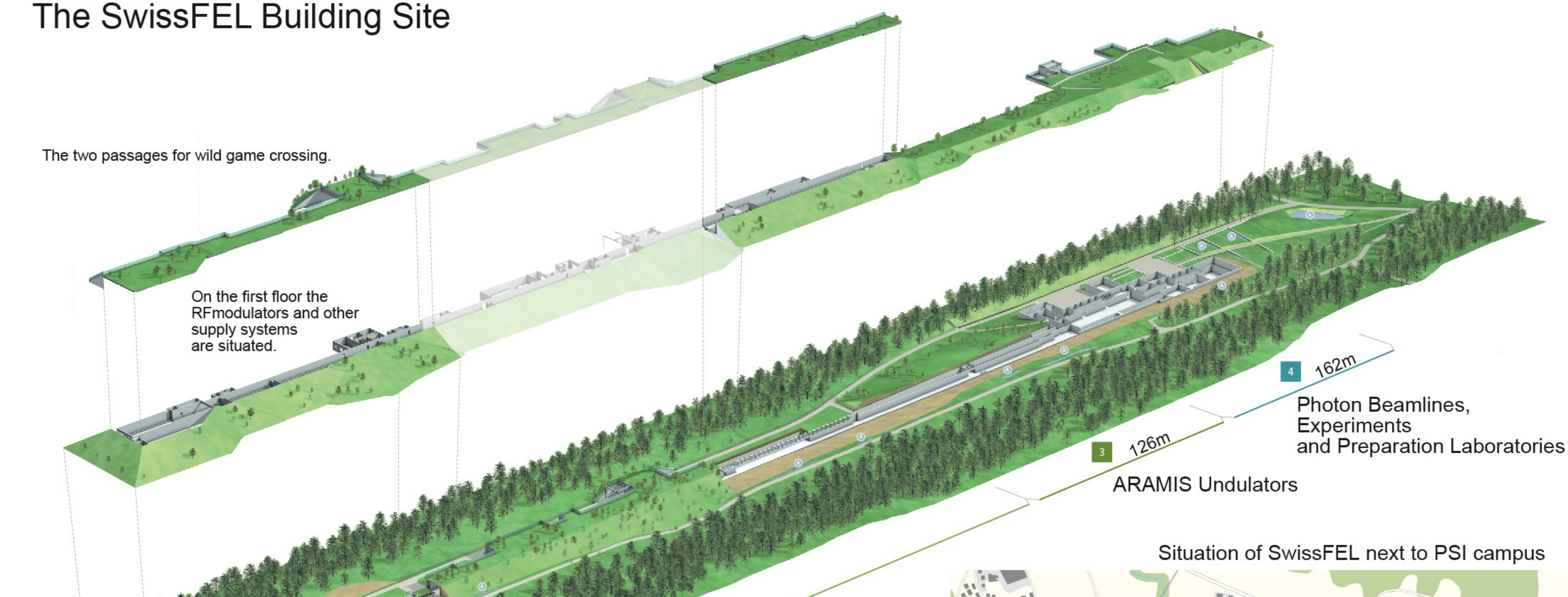
- The SwissFEL Project

- Beam and Photon Brillance
- Collective Effects in SwissFEL Linac
- SwissFEL Optimization and Layout Consideration

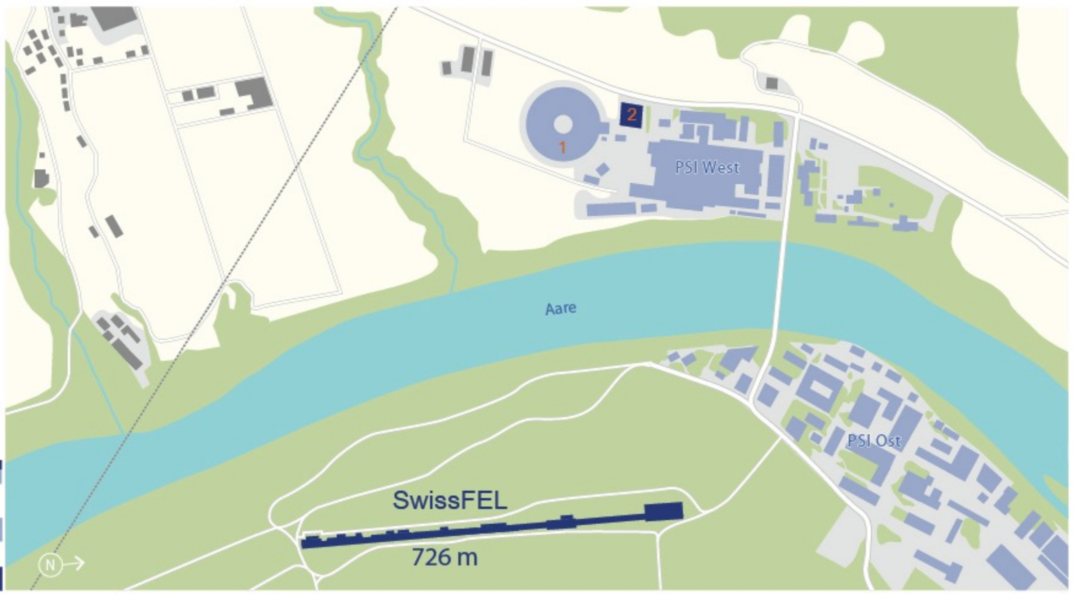
- Magnets in SwissFEL
  - Dipoles
  - Quadrupoles
  - Solenoid
  - Corrector Magnets

- Conclusion

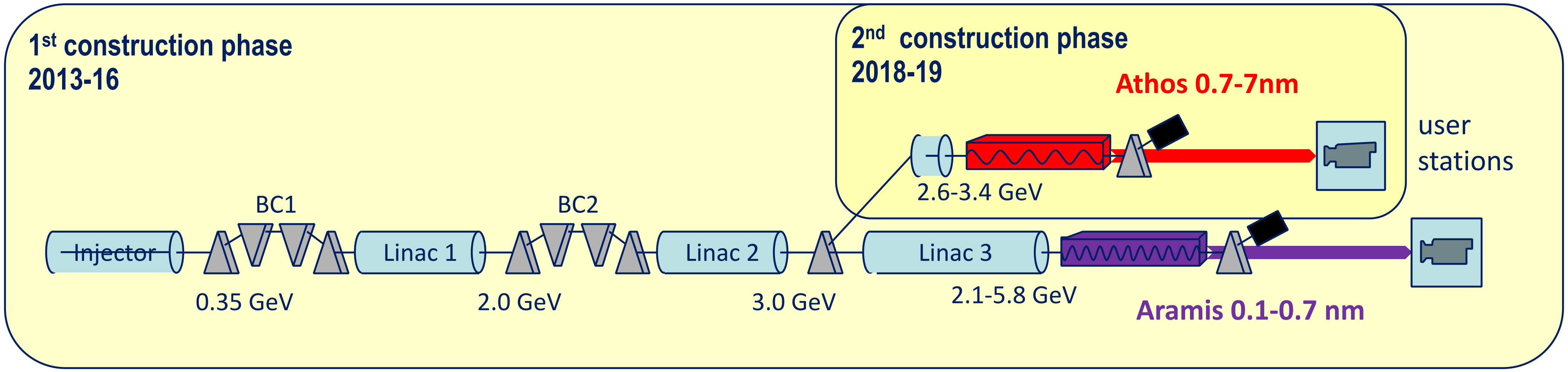
The SwissFEL Building Site



Situation of SwissFEL next to PSI campus



SwissFEL Schedule



Advanced project funding
(from ETH Domain & economic stimulus package)

BFI finance period

Next finance period

2012	2013	2014	2015	2016	2017
component procurement accelerator and ARAMIS FEL				preparation ATHOS FEL	
prepatory work	building construction		Accelerator and ARAMIS FEL installation	commissioning	friendly users

Photon and Electron Beam Brilliance and Brightness

Photon Peak Brilliance

$$B_{ph} = \frac{\#\text{photon}}{\sigma_t \sigma_x \sigma_{x'} \sigma_y \sigma_{y'} (\Delta\omega/\omega)}$$

Electron Beam Peak Brilliance

$$B_{el} = \frac{\#\text{electron}}{\sigma_t \epsilon_x \epsilon_y (\Delta E/E)}$$

Extraction Efficiency ρ of FEL

$$\frac{\#\text{photon}}{\sigma_t} \propto P_{sat} \approx \rho P_{beam} \propto \rho\gamma \frac{\#\text{electron}}{\sigma_t}$$

Beam Requirements for Lasing:

- Electrons can radiate into diffraction limited radiation mode

$$\epsilon_x < \sigma_x \sigma_{x'} = \frac{\lambda}{4\pi}$$

- Landau damping is not preventing the formation of FEL micro bunches

$$\frac{\Delta E}{E} < \rho \approx \frac{\Delta\omega_{sase}}{2\omega}$$

FEL converts electron brilliance into photon brilliance

Optimization of FEL Efficiency (FEL Parameter)

FEL Parameter

$$\rho = \frac{1}{\gamma}\left(\frac{f_c^2 K^2}{k_u^2}\frac{1}{2I_A}\frac{I}{\bar{\beta}\sqrt{\epsilon_x\epsilon_y}}\right)^{\frac{1}{3}}$$

The focusing β is reduced till the induced axial velocity spread affects the FEL process by Landau damping

$$\bar{\beta} \approx \frac{\lambda_u}{4\lambda}\frac{\epsilon_x + \epsilon_y}{\rho}$$

The compression and thus peak current is limited when the induced energy spread affects the FEL process. This is when the energy spread is comparable to the FEL parameter

$$\frac{I}{\bar{\beta}\epsilon} \propto \rho\frac{I}{\epsilon^2} \propto \rho^2 B_{el}$$

With optimization the FEL parameter scales with electron brilliance

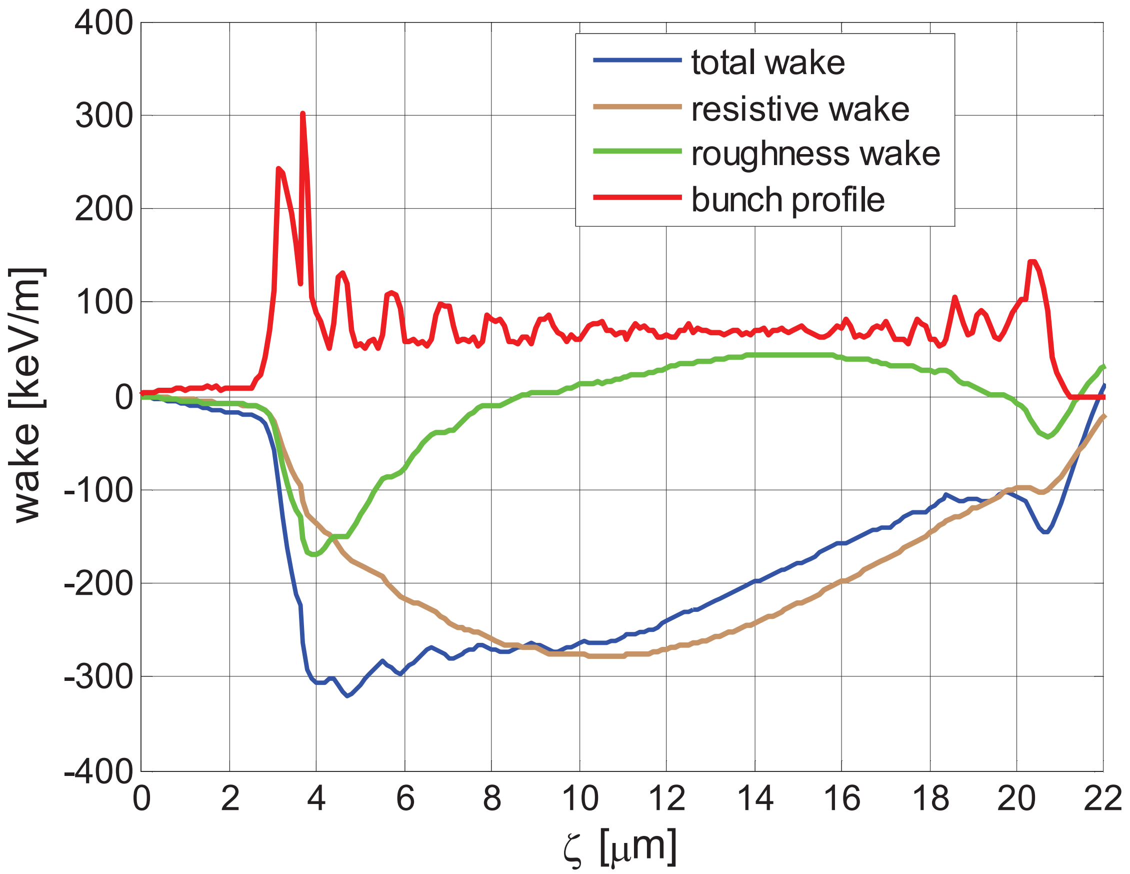
SwissFEL Specific Optimization

Major point of optimization was the facility length while reaching 1 Angstrom.
Driving point was the in-vacuum undulator technology to minimize the undulator period.

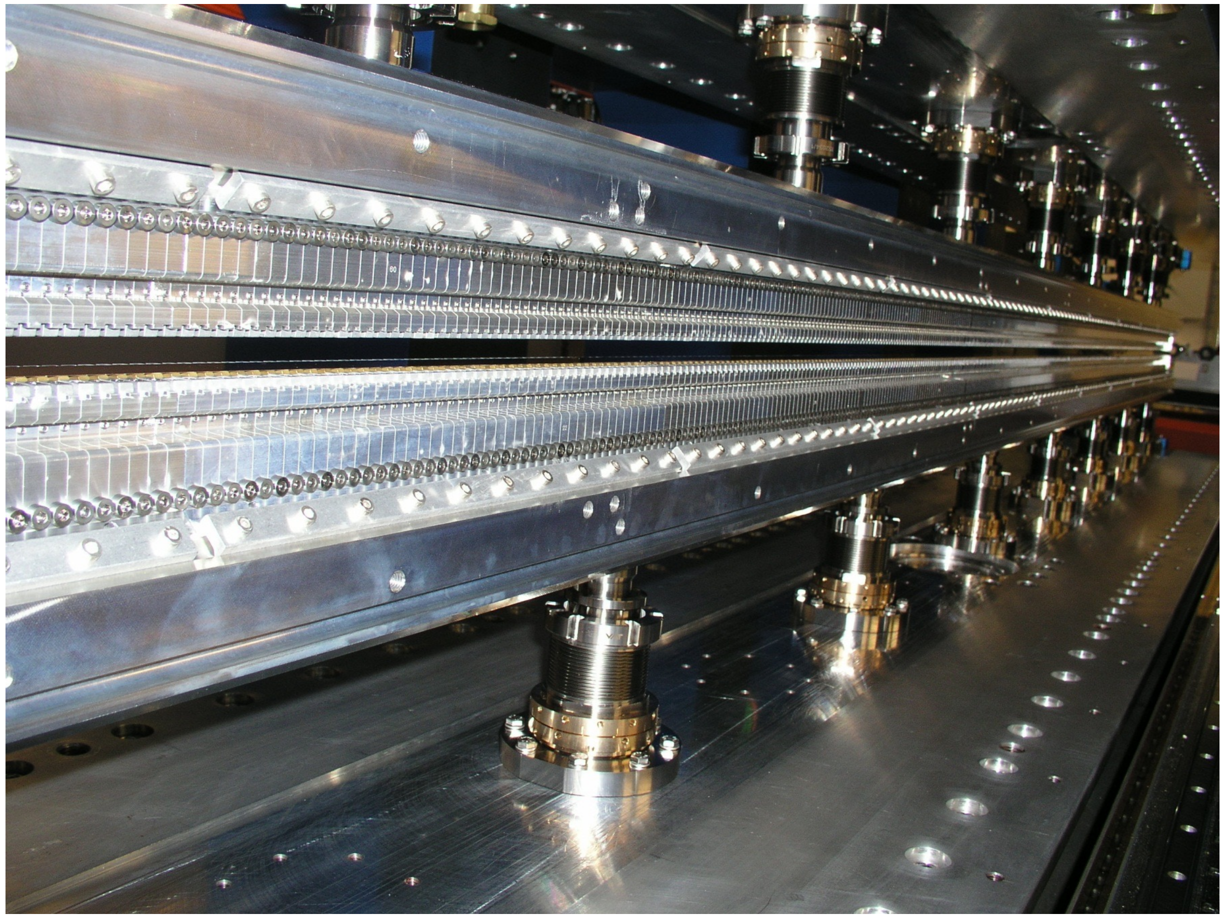
$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

With an undulator period of 15 mm and an undulator parameter of K=1.2 the required beam energy is 5.8 GeV

Undulator Wakes (Courtesy E. Prat)

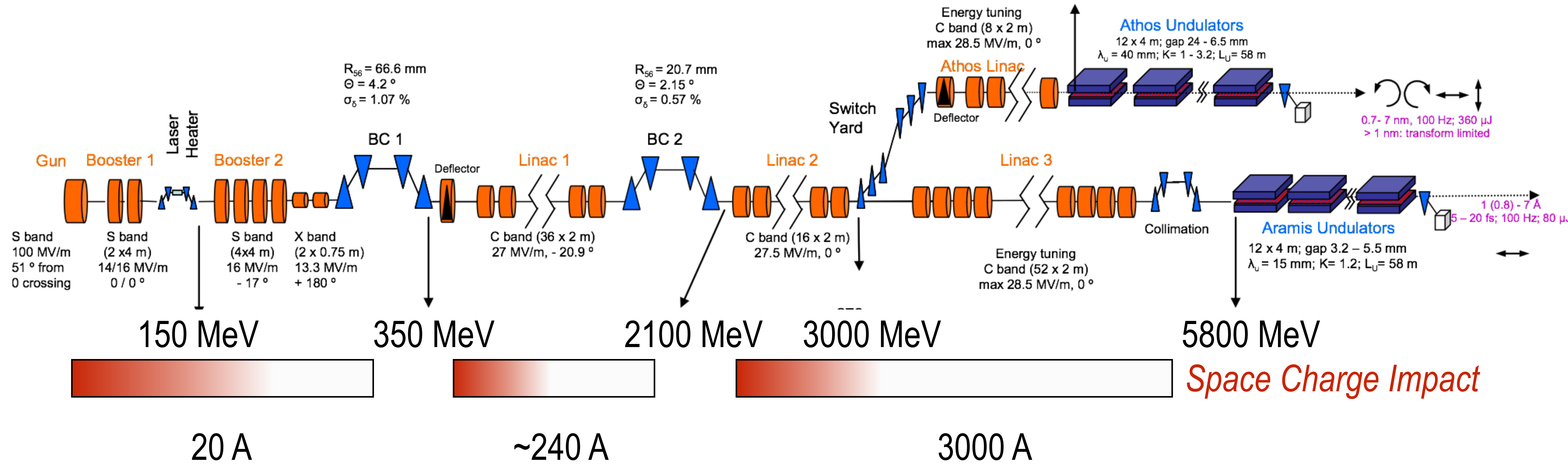


U15 Prototype (Courtesy T. Schmidt)



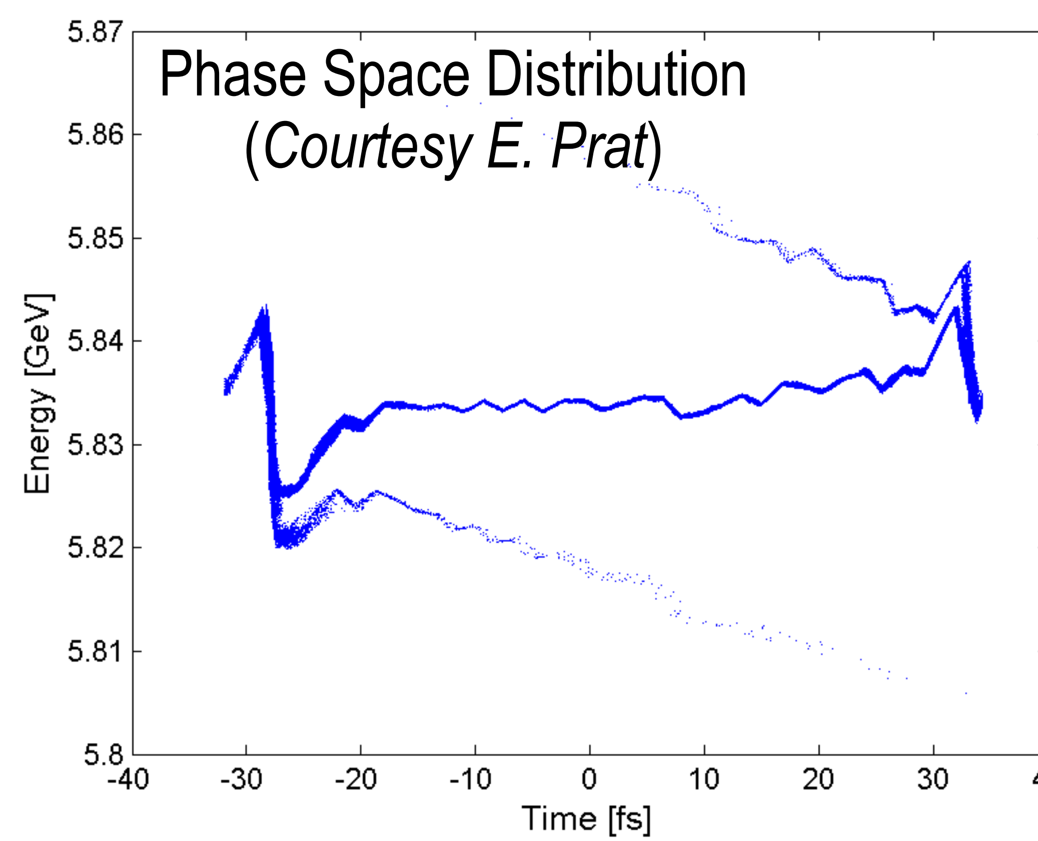
A current of 3 kA allows a rather flat wakefield potential, which can be efficiently compensated by undulator taper Stronger compression would yield a chirp and only a short section could stay in resonance.

Two-Stage Compression Scheme



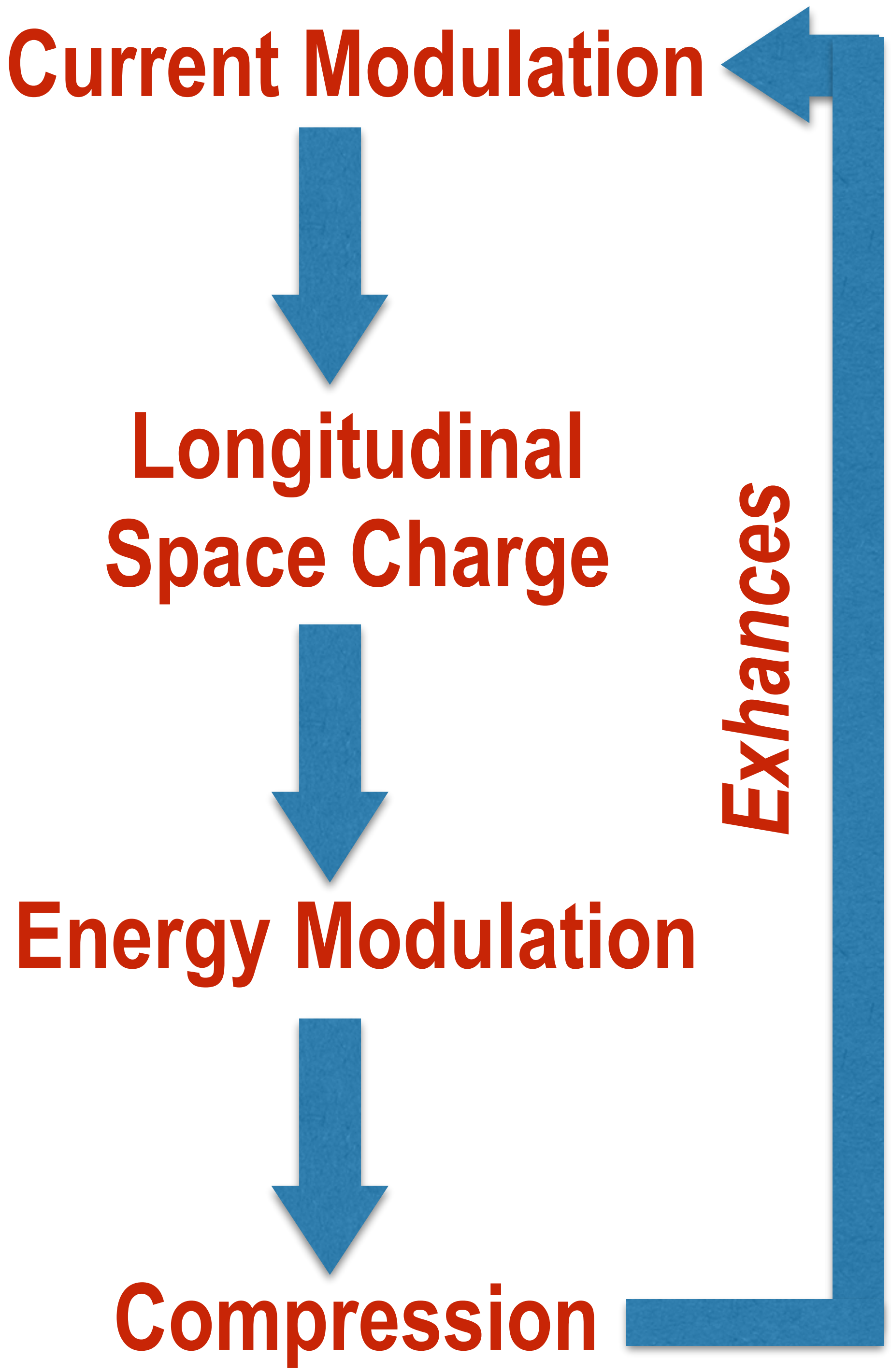
Two stage compression scheme:

- Flat current profile with 3 kA for 200 pC
- Removal of residual chirp at undulator entrance
- Total compression factor C=C1*C2=150
- Individual compression C1 free for optimization
- Dipole chicanes with rather small bending angle

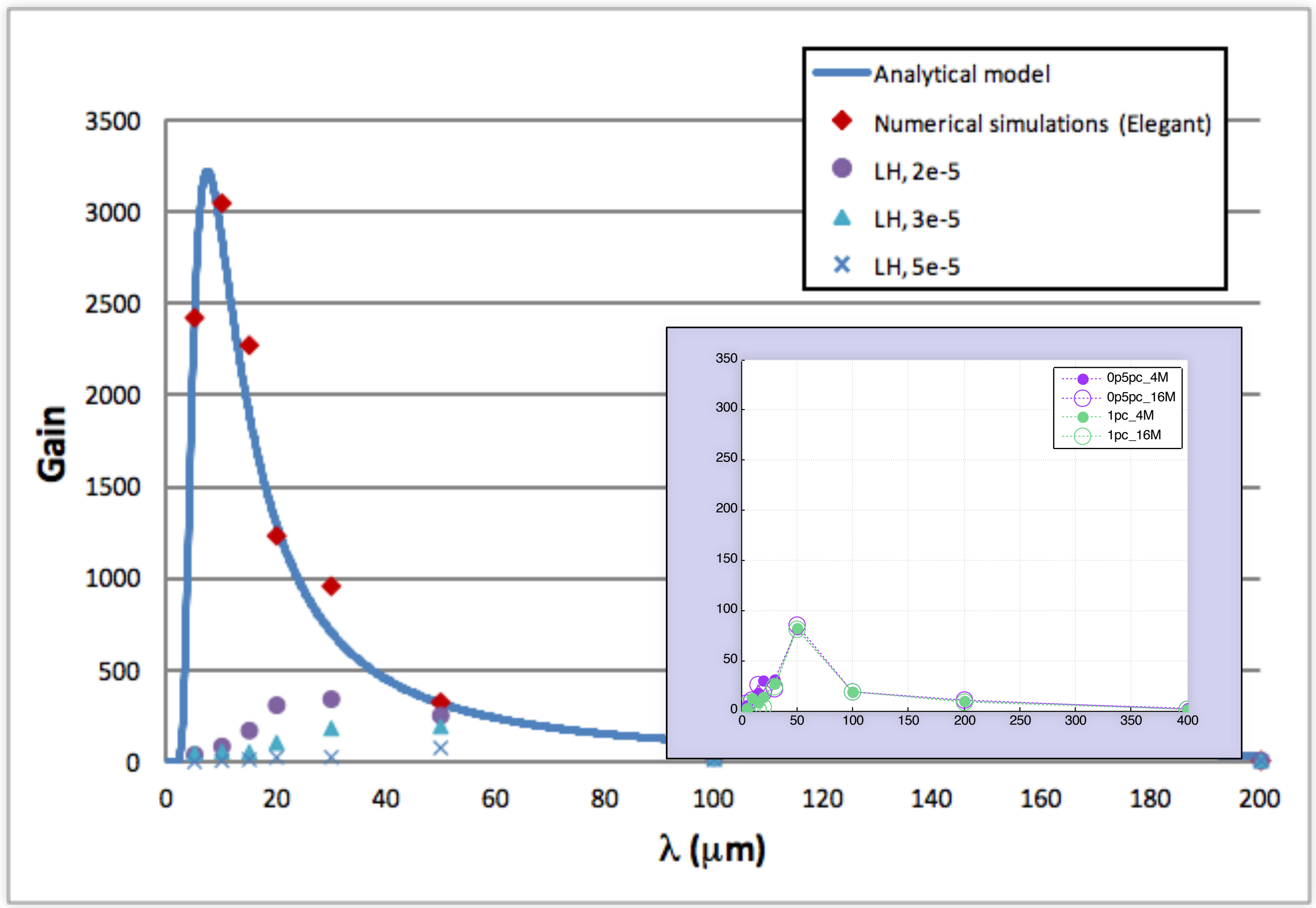


Microbunch Instability

A high brilliant electron beam is sensitive to microbunch instability in a multi stage compression scheme.



Microbunch Instability (Courtesy S. Bettoni)

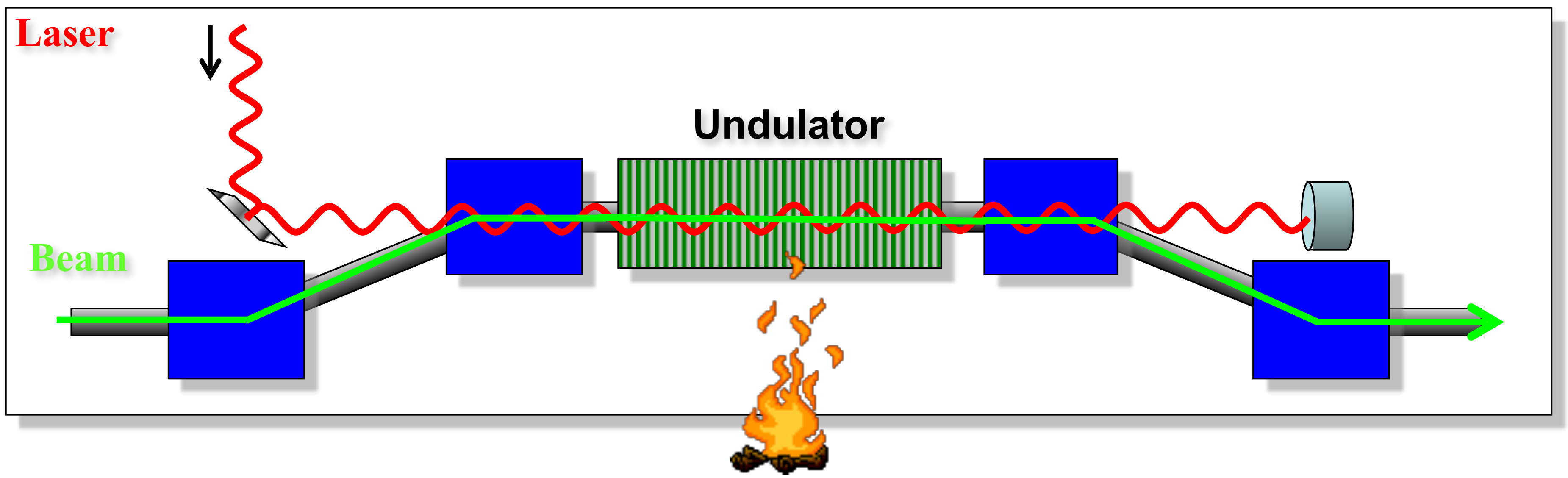


Laser Heater

With a compression factor of C=150 and an acceptable energy spread of 600 keV the initial energy spread could be up to 4 keV, much larger than typical energy spread from RF Guns.

Increase initial energy spread to 4 keV with Laser Heater

Laser Heater Schematic (Courtesy Z. Huang)



Laser peak power

Beam size

$$\Delta\gamma_L(r) = \sqrt{\frac{P_L}{P_0}\frac{K L_u}{\gamma_0 \sigma_r}}[\mathrm{JJ}]\exp\left(-\frac{r^2}{4\sigma_r^2}\right)$$

Laser rms spot size

The induced energy modulation is over compressed after first compression stage and treated as uncorrelated energy spread.

FELs would greatly benefit from reversible „heater“ to avoid this unwanted spoil of the beam brilliance. Most proposed ideas (e.g. emittance exchange) are rather impractical in their technical realization

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Spectrometer Dipoles

	Length	Angle	Beam Energy
Gun	25 cm	30	7 MeV
Injector	1 m	20	0.1-1 GeV
Aramis	2 m	8	2.0-6.0 GeV
Athos	1.1 m	8	2.5-3.5 GeV

All spectrometer are followed by quadrupoles to:

- increasing dispersion for finer energy resolution with BPM Screen
- decrease dispersion to guarantee beam transport to dump with large energy spread

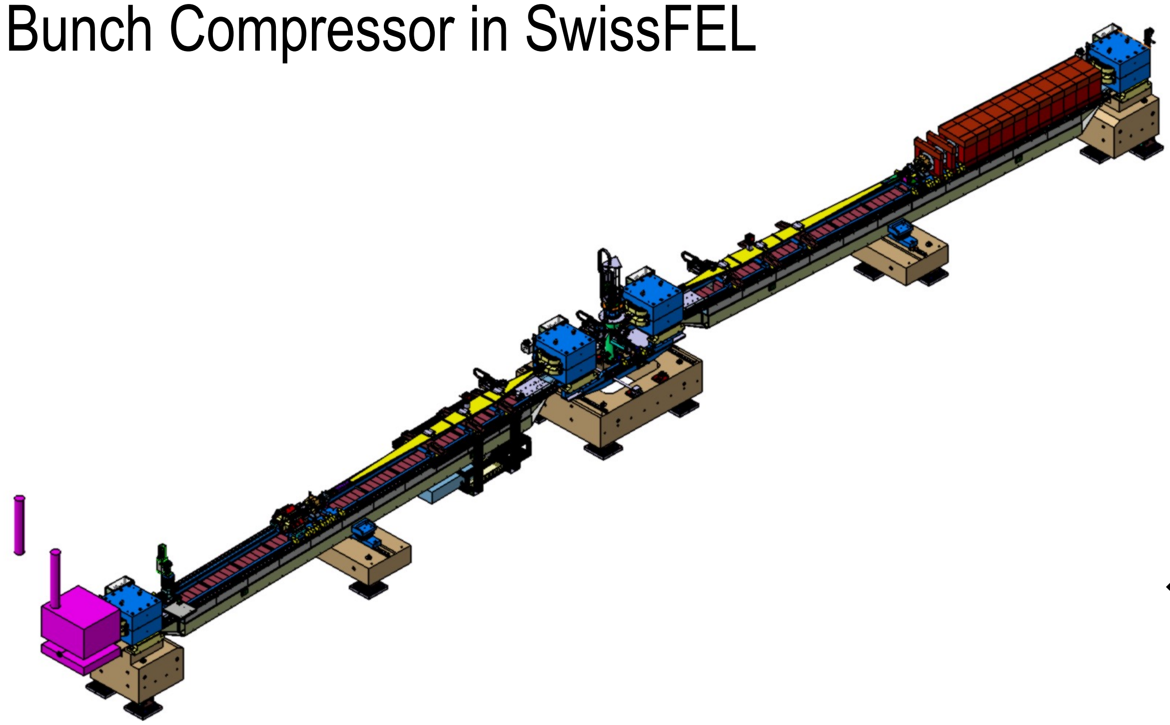
Spectrometer needs active energy calibration

but

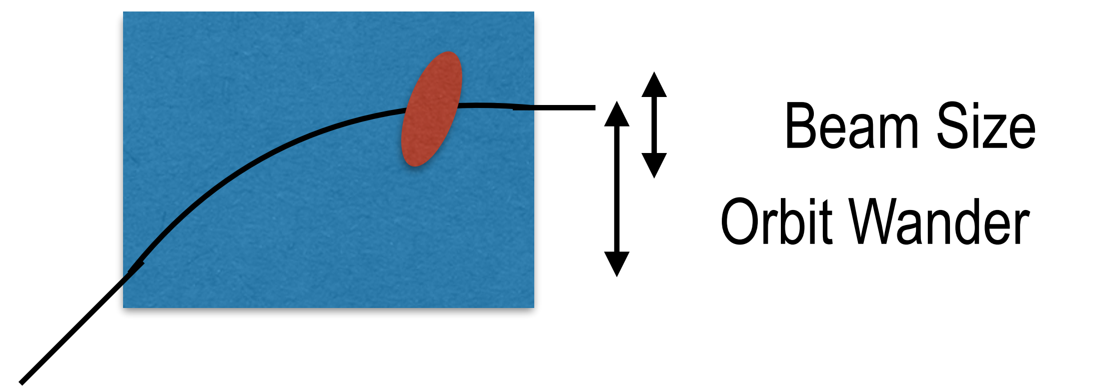
**Reduces requirement for good field region,
simplifying spectrometer design**

Bunch Compressor Chicanes

Bunch Compressor in SwissFEL



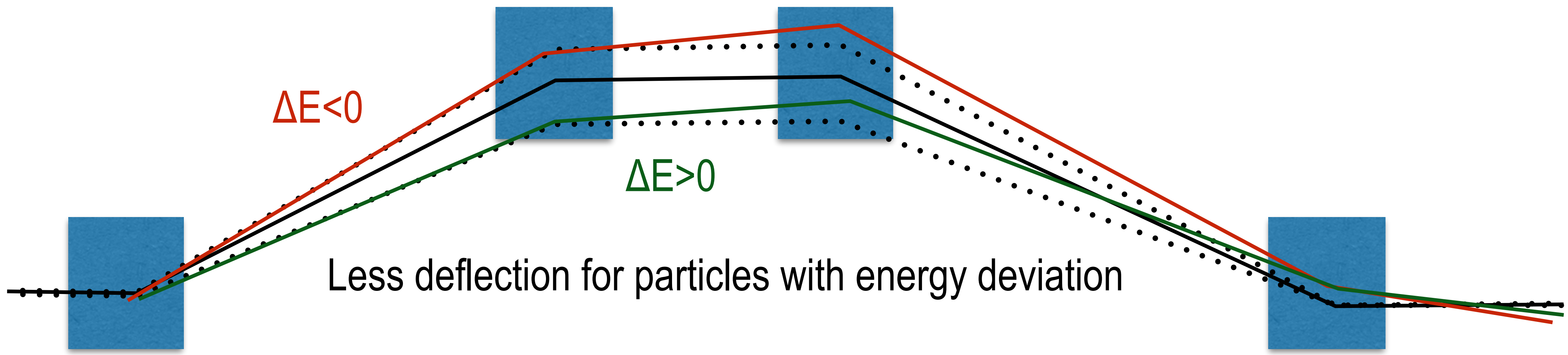
Orbit in Inner Dipoles

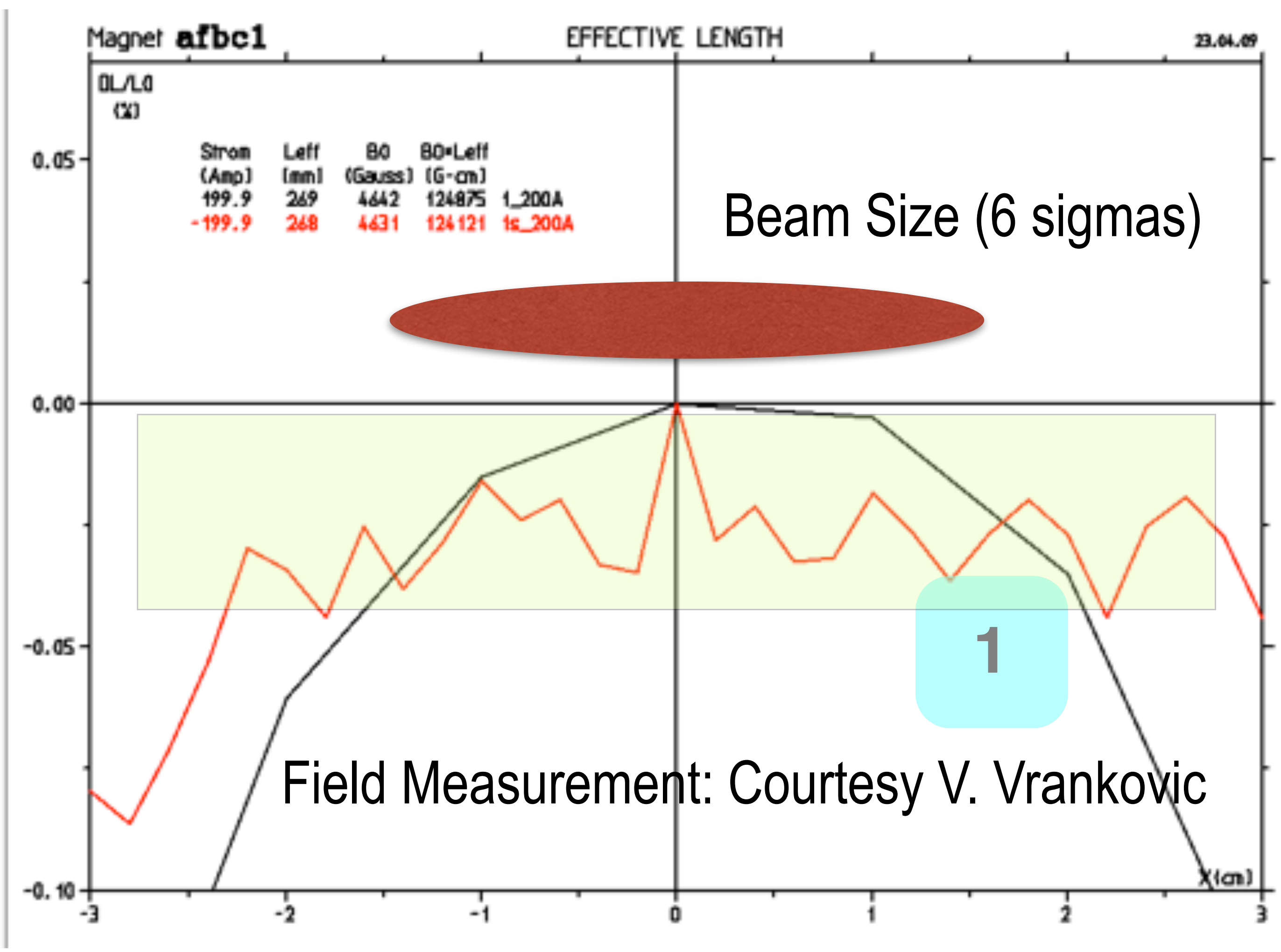


For first bunch compressor (L_b=25 cm, θ=4 degree)

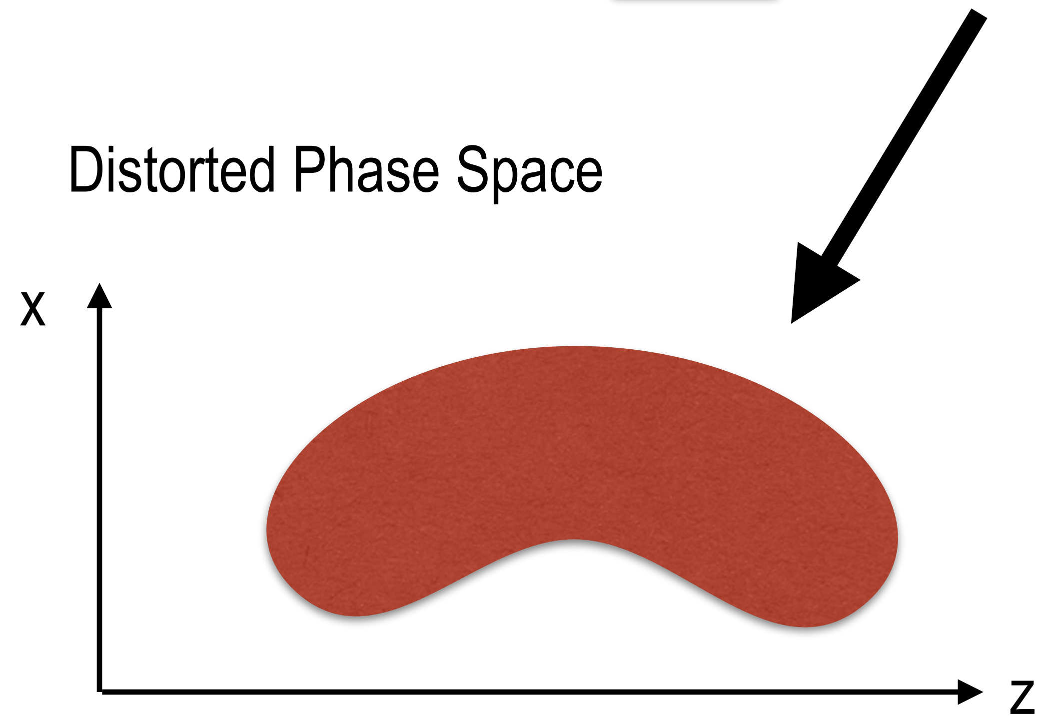
- Orbit Wander: $L_b \frac{1-\cos\theta}{\sin\theta} \approx 8.7 \text{ mm}$ Net kick for all electrons the same. Simple correction
- Beam Size: $\eta \frac{\sigma_E}{E} \approx 5.6 \text{ mm}$ Position dependent kick. Difficult correction

Good Field Requirement for Dipole Magnets





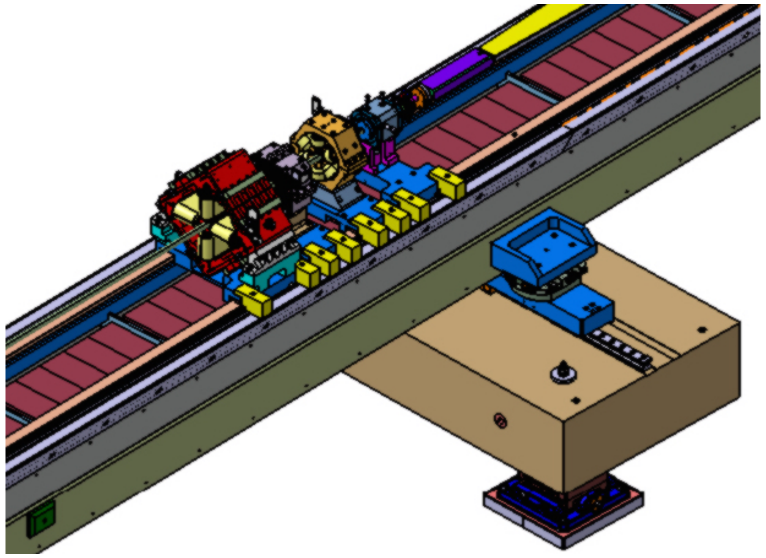
Distorted Phase Space

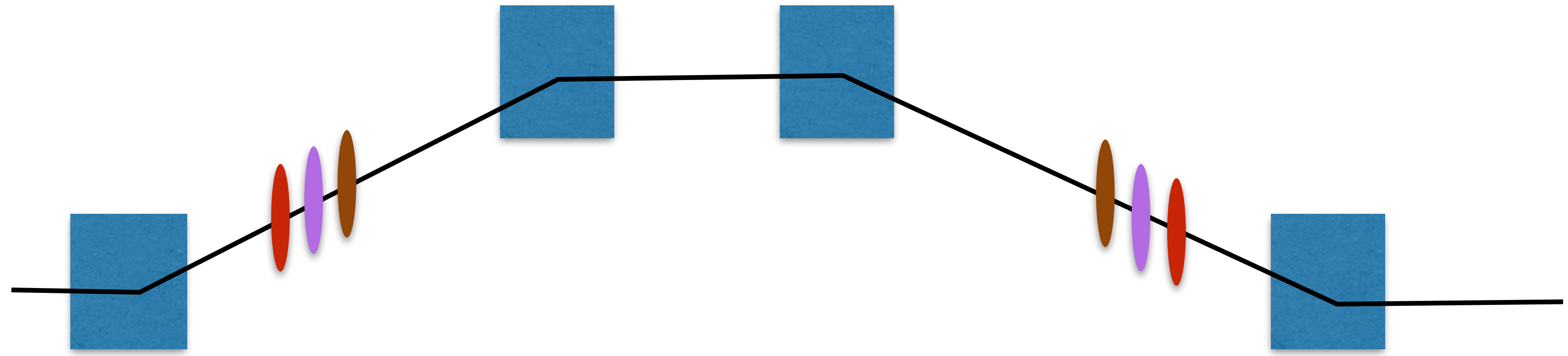


Leads to increase of projected emittance

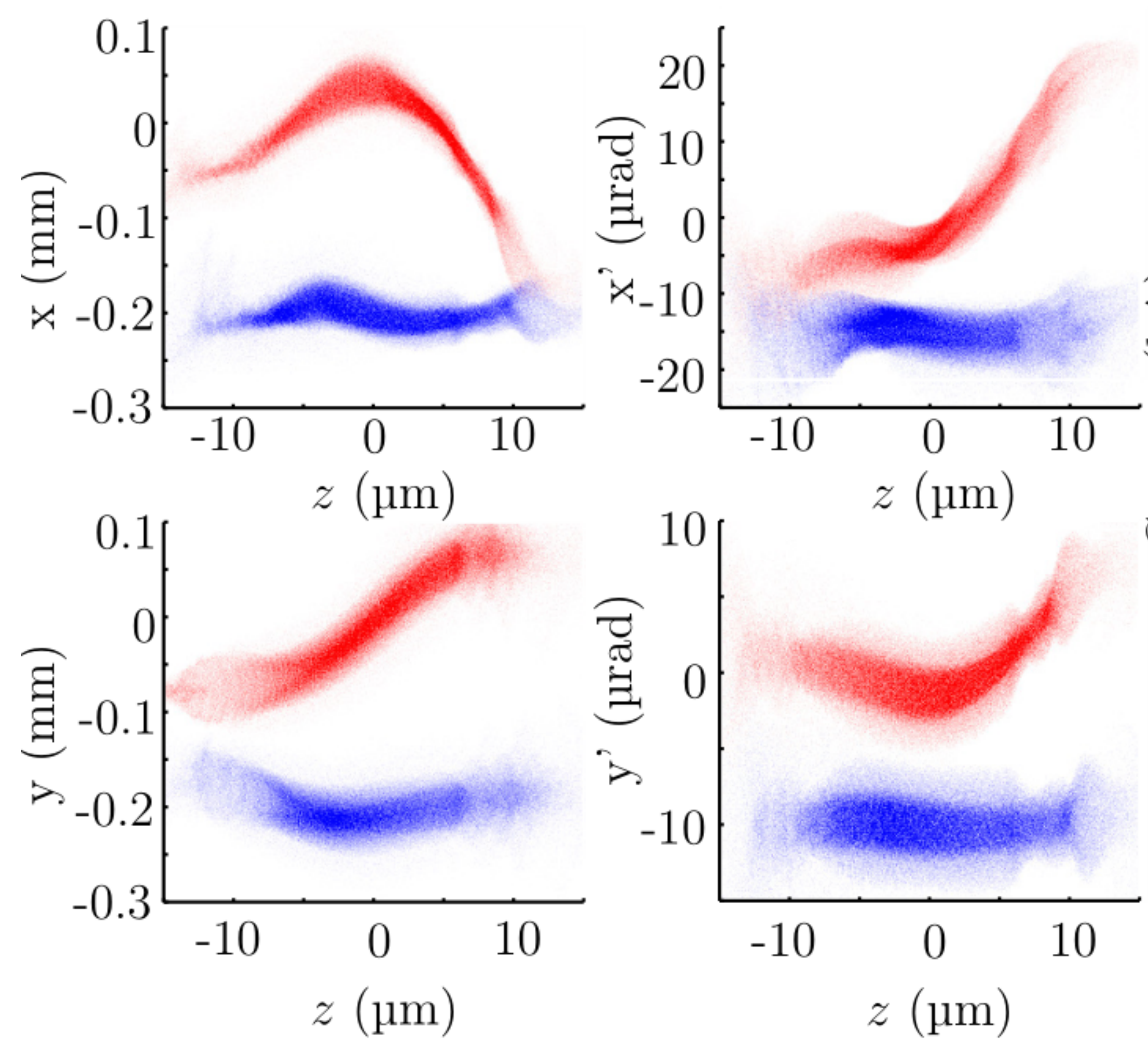
$$\Delta x' \approx \frac{2eB_o}{\gamma mc}(L_{eff}(x) - L_{eff}(0)) \ll \sqrt{\frac{\epsilon_n}{\gamma\beta}}$$

Active Correction of Beam Tilts in SwissFEL





Correction for SwissFEL *(Courtesy M. Guetg)*



Corrector Magnets:

- Quadrupole
- Skewed Quadrupole
- Sextupole

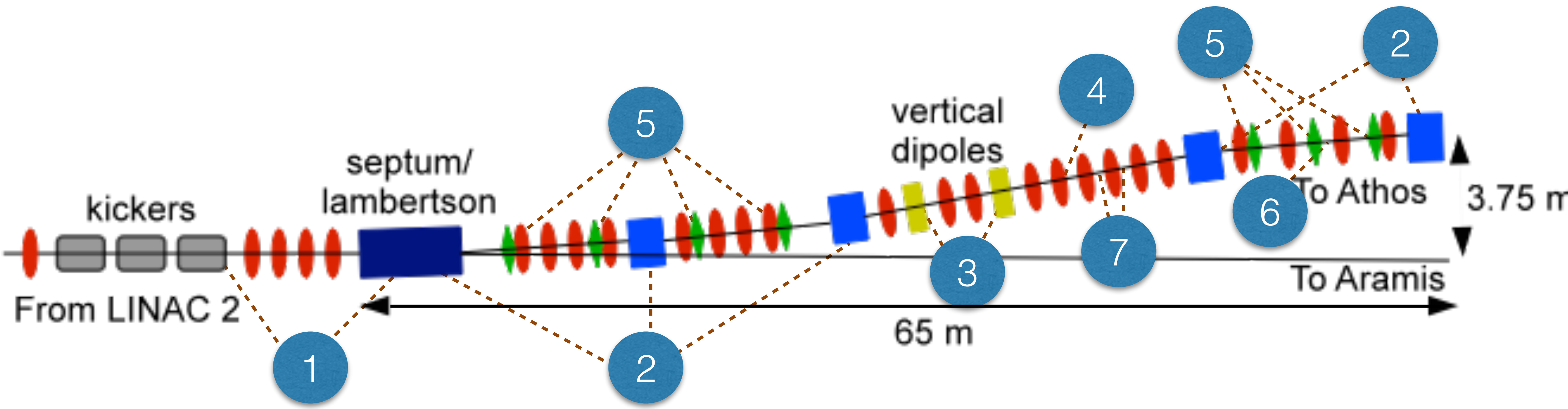
Position balanced between

- Large dispersion (limited by vacuum chamber)
- Reduced corrector strength for offsets

In SwissFEL the corrector magnets are not only used to compensate for field errors but also to align tilted electron beams due to:

- CSR effects
- Wakefields
- Field Errors

SwissFEL Switchyard Optimization

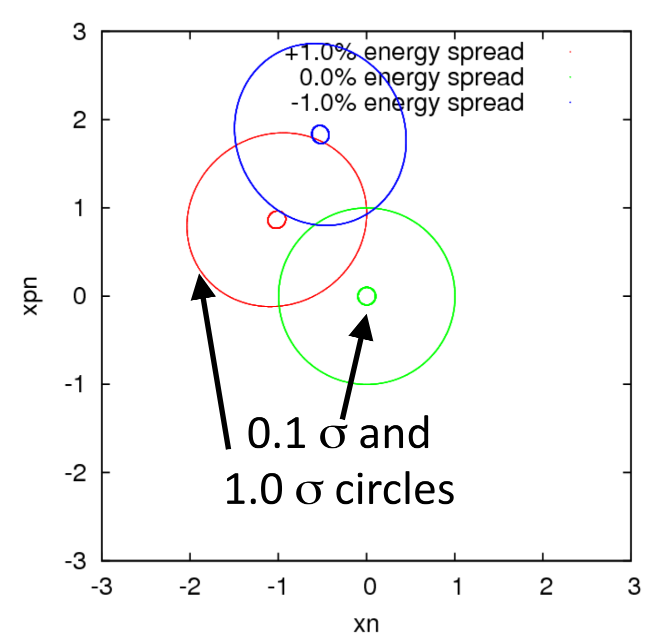


Optimization Tasks:

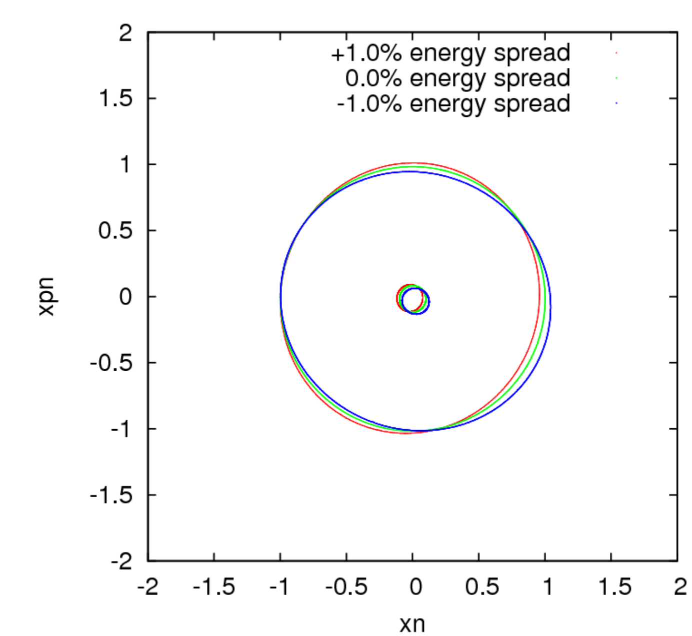
1. Extract second bunch with septum
2. Net bend of 5 degree
3. Vertical dogleg to go back to reference height
4. Adjust phase advance to compensate CSR
5. Increase energy acceptance with sextuples
6. Allow for energy collimation
7. Allow for beam chirp removal

Courtesy N. Milas

Before Sextuple correction



After Sextuple correction



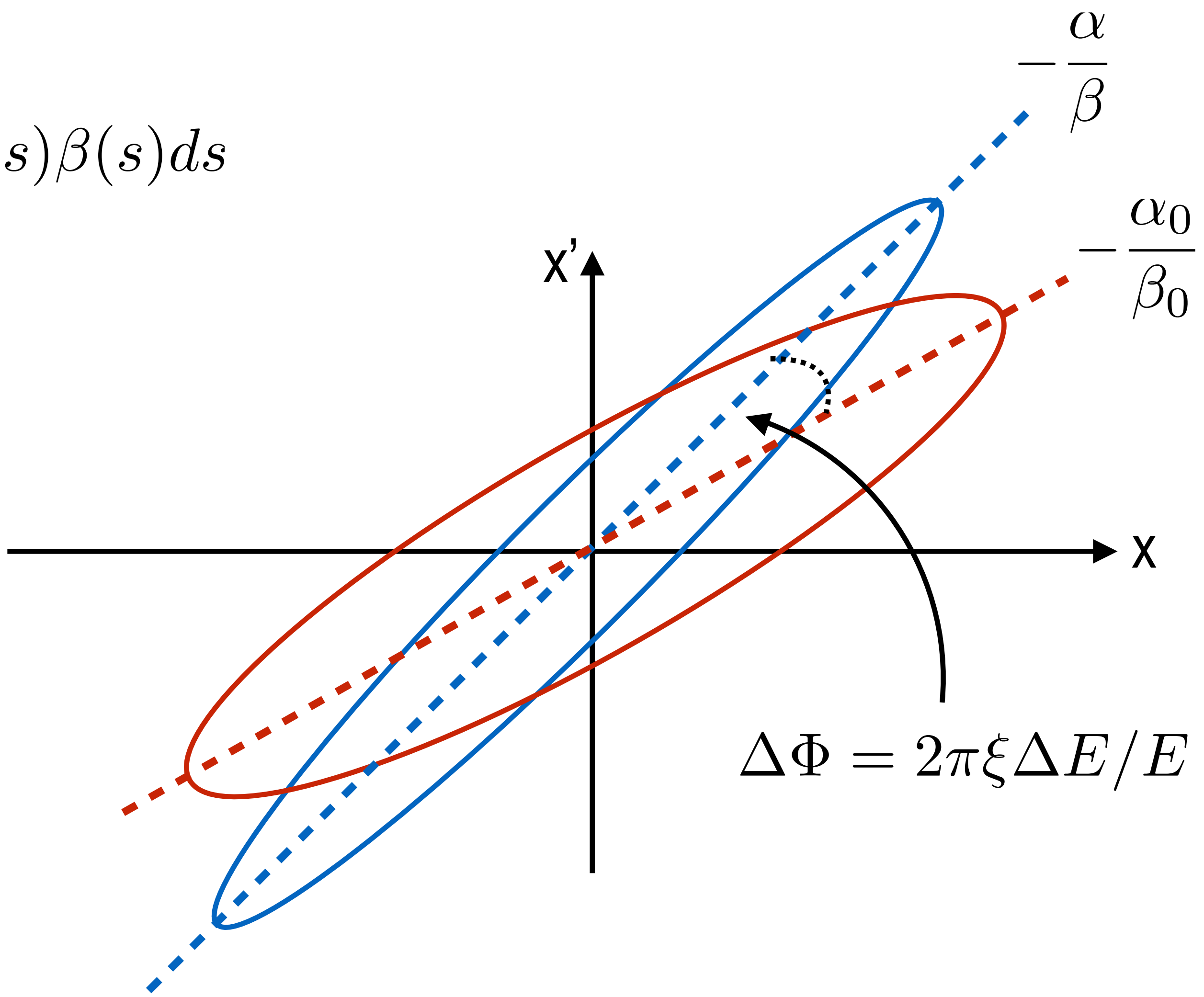
Quadrupoles in SwissFEL - Chromaticity

Due to large energy variation of a few percents around bunch compressor, the beta ton phase advance has an energy dependence, given by the chromaticity

$$\xi = -\frac{1}{4\pi}\int k(s)\beta(s)ds$$

For a linac this translates to a mismatch along the bunch

$$\zeta = \frac{\beta(s)\gamma_0 + \beta_0\gamma(s) - 2\alpha(s)\alpha_0}{2}$$



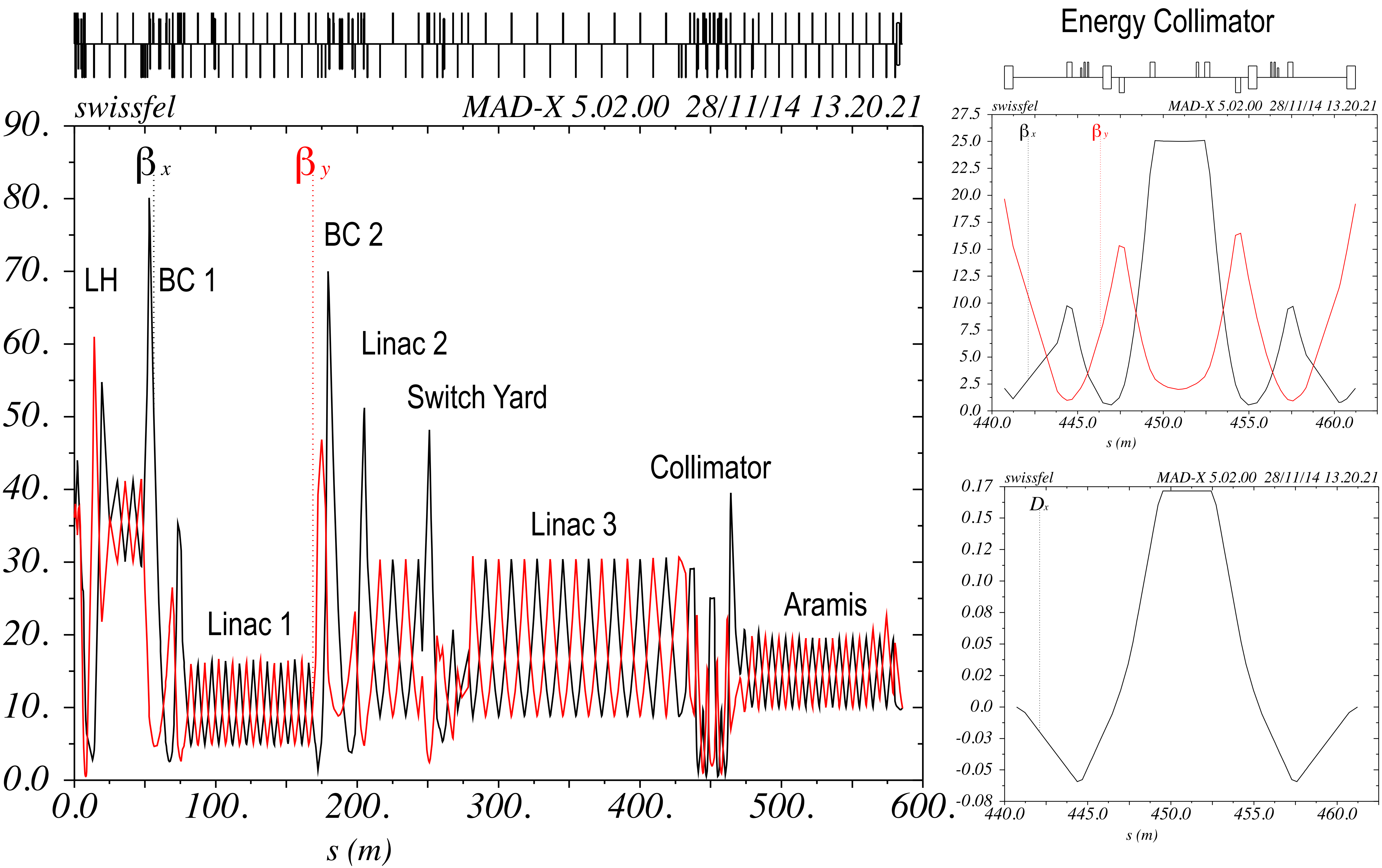
Design Optics Optimization:

- Keep beta-function small at matching section
- Keep focussing strength small
- Optimize quad position and number

but

- Allow large beta-function at BC's entrance
- Keep overall facility length compact

SwissFEL Optics



Solenoids

Used in low energy section of SwissFEL to control beam envelope up to 150 MeV.

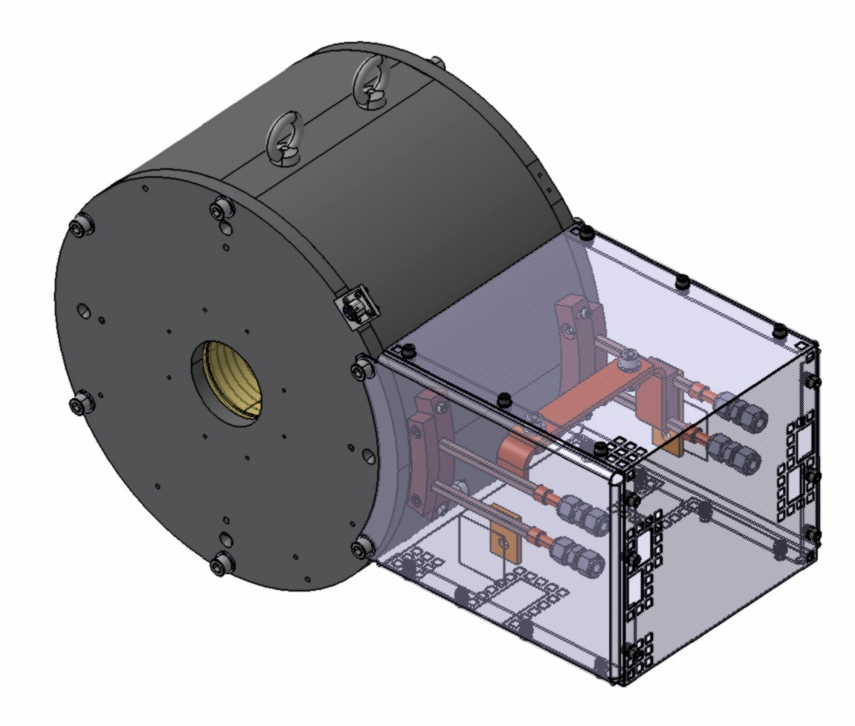
Ideal case: Beam has round symmetry and any rotation does not change the beam parameters

Real case: No fully symmetric windings of solenoid as well as RF quadrupole components break the symmetry and coupling is introduced.

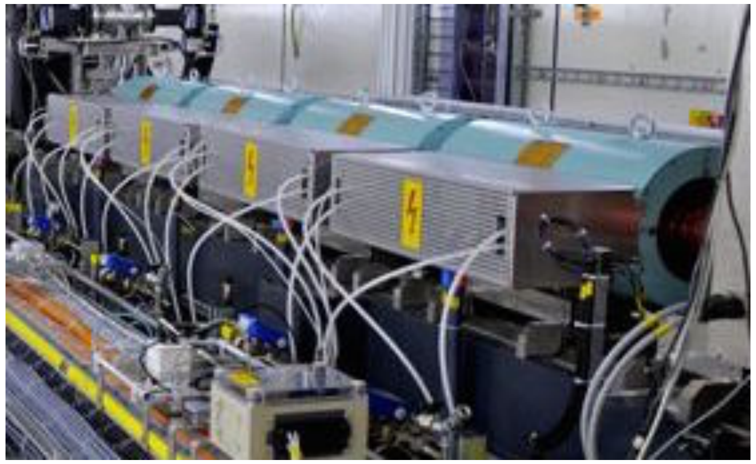
Solution:

- Integration of corrector quadrupole and skew quadrupole in gun solenoid.
- Additional corrector quadrupoles (see next slides)
- Alternating polarity of Booster solenoid to „unrotate“ beam
  - With energy gain entrance and exit kick do not cancel.
  - Stronger fields for succeeding solenoids

Gun Solenoid

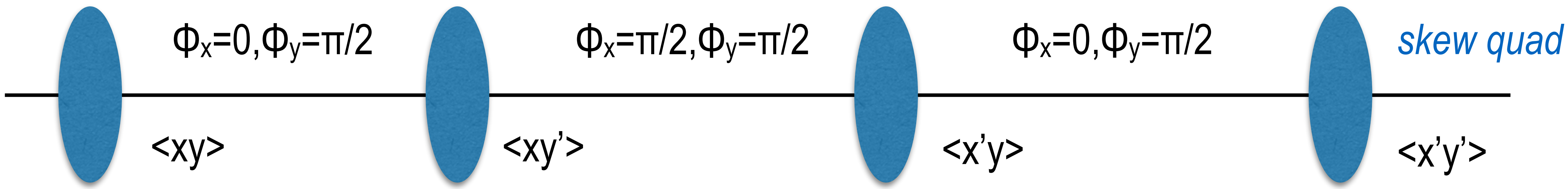


Booster Solenoid

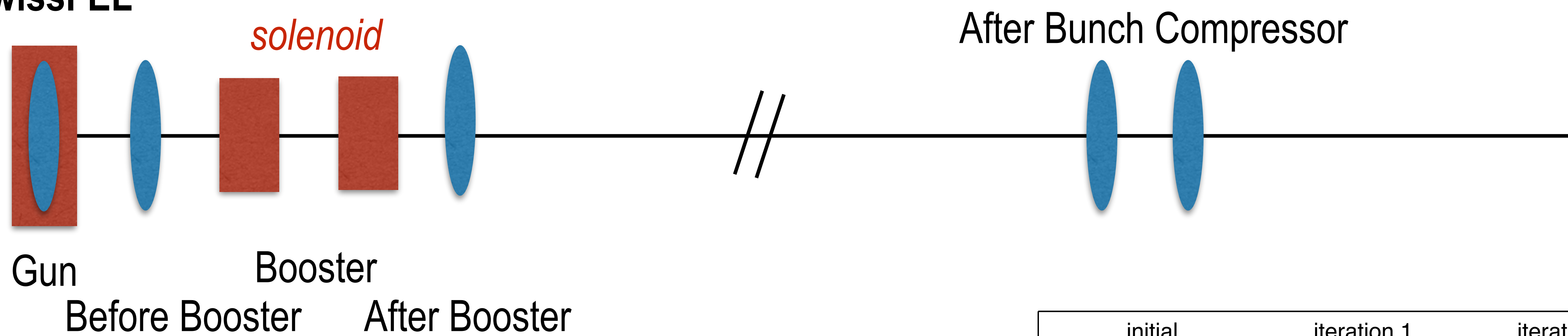


Coupling Correction - Skew Quadrupoles & Solenoids

Ideal



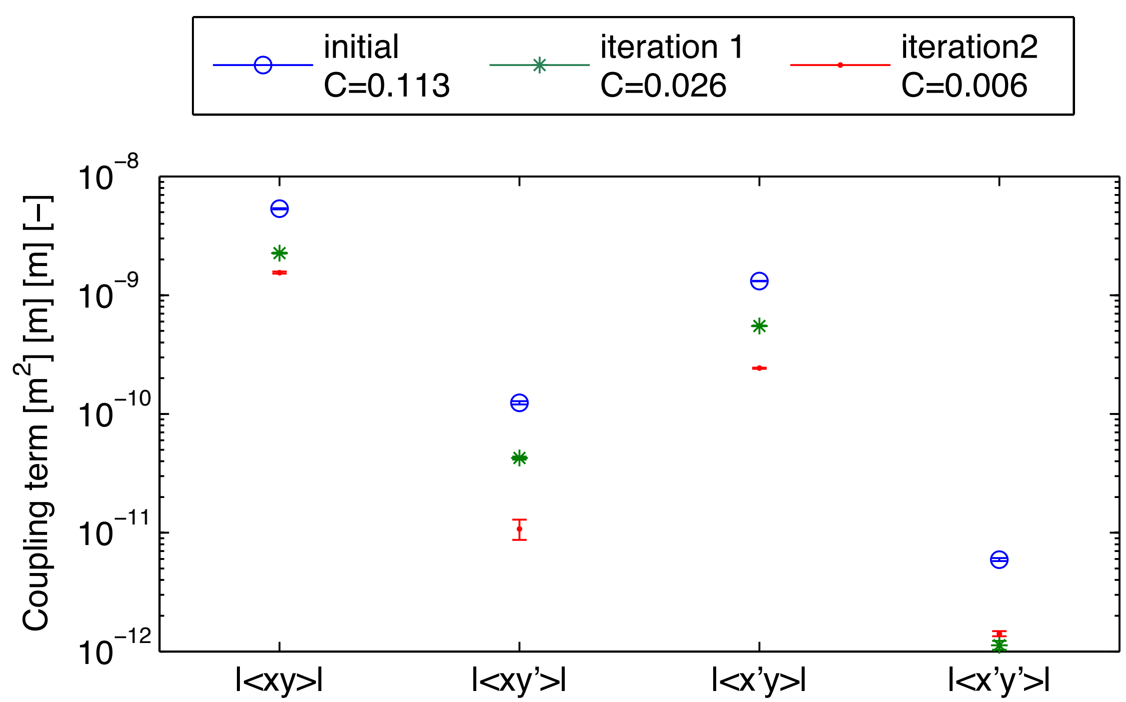
SwissFEL



Emittance Optimization (*Courtesy M. Aiba and E. Prat*)

1. Measure response **S** of coupling to all coupling magnets
2. Invert **S** with SVD to set corrector values **C**

$$\vec{C} = S^{-1} \begin{pmatrix} < xy > \\ < xy' > \\ < x'y > \\ < x'y' > \end{pmatrix}$$



Conclusion

Beam Brightness and Optimization

- High brightness needed to drive FEL, in particular at lowest energy possible for 1 Ångstrom FEL
- Uniformity of bunch parameter along the bunch enhances FEL efficiency
- Prevent active degradation by
  - Microbunch Instability
  - Wakefields
  - Coherent Synchrotron Radiation
- Electron quality „too good“ and can be spoiled for better beam transport

Magnet Tolerances & Specification

- Rather relaxed due to the single pass nature of the machine, except for
  - Inner dipoles in magnetic chicanes due to the transverse beam size
  - Solenoids in gun and booster region causing beam coupling
- Active correction with skew quads and sextupoles, also used for beam manipulation on slice level