DISPERSION BASED BEAM TILT CORRECTION

Marc Guetg

Paul Scherrer Institut

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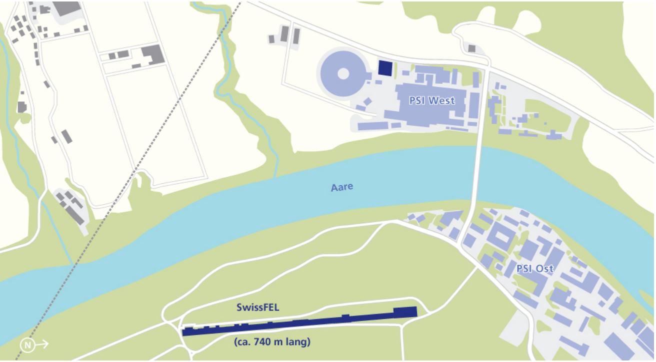
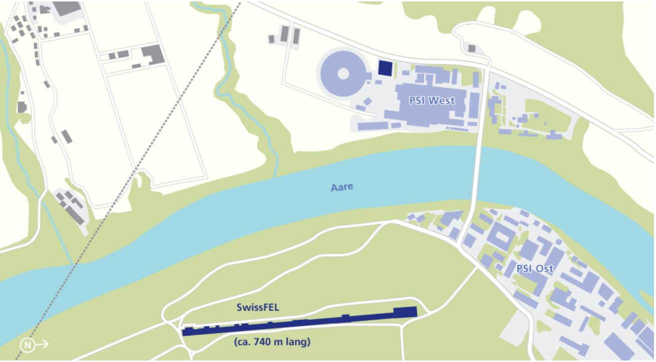
PSI



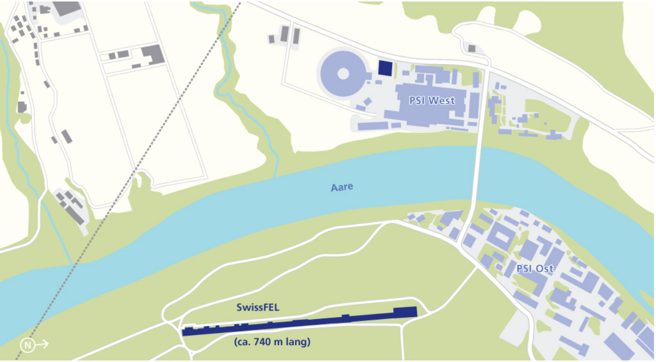
- HIPA

PSI



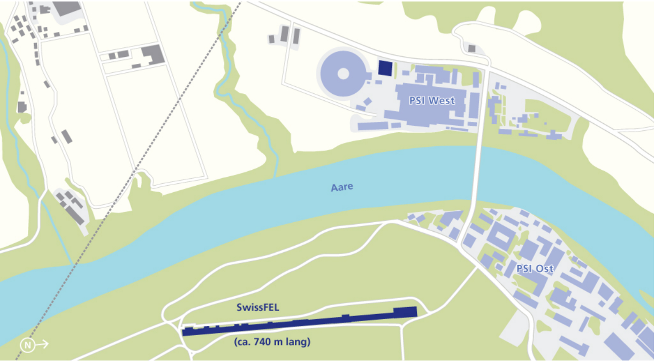
- HIPA
- SINQ

PSI



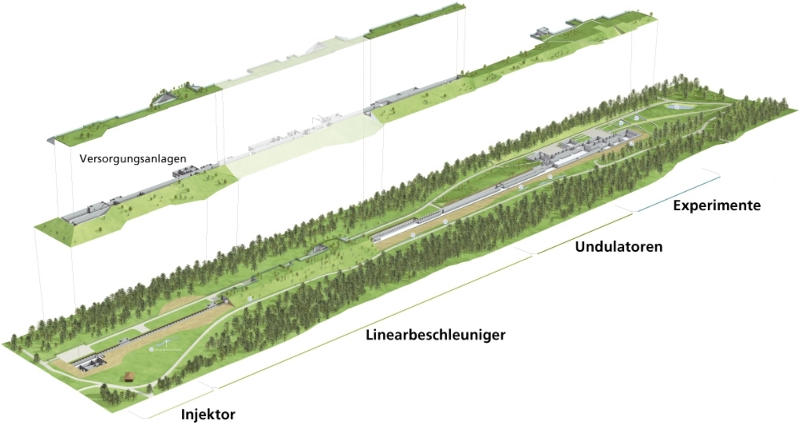
- HIPA
- SINQ
- SLS

PSI



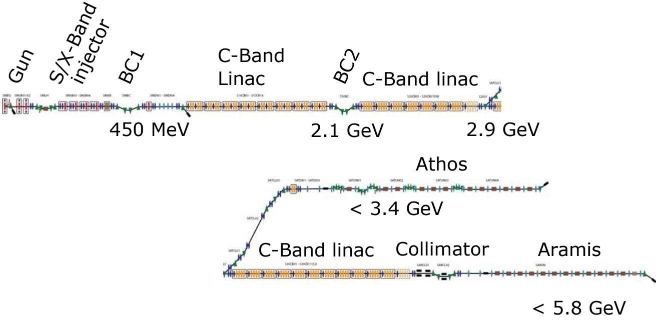
- HIPA
- SINQ
- SLS
- SwissFEL

SwissFEL


Versorgungsanlagen
Experimente
Undulatoren
Linearbeschleuniger
Injektor

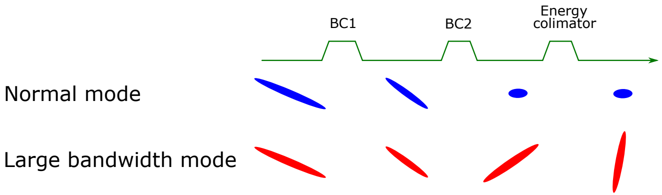
SwissFEL

Operation mode



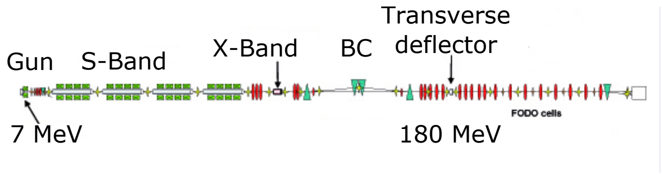
- Undulator period 15 mm
- Saturation pulse energy 60 μJ
- Saturarion power 2 GW
- ø brightness $2 \cdot 10^{21}$ $\#photons/mm \cdot mrad^2 \cdot s \cdot 0.1\%$ bandwidth

Operation parameters



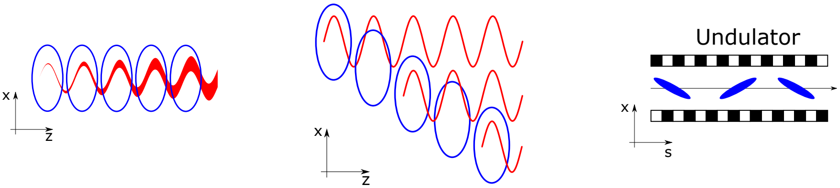
	Short pulse	Long pulse	Large bandwidth
Charge [pC]	10	200	200
σ_z [fs]	2	25	22
Compression	533	125	–136
$\varepsilon_{\text{slice}}$ [nm]	180	430	430
Peak current [A]	830	3000	3970

SwissFEL injector test facility



- Test procedures
- Test components

Motivation



Slice centroid oscillation reduces overlap between electron and radiation

- Reduces FEL performance

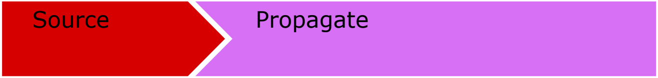
Increases spot size $\rightarrow \varepsilon_{projected}$

- Discrepancy between $\varepsilon_{projected}$ and ε_{slice} increases

Correction of centroid misalignment

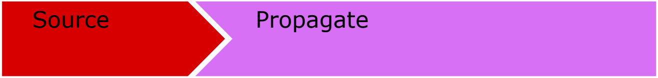
- Kick: $x_c'(z)$

Correction of centroid misalignment



- Kick: $x_c'(z)$
- Propagate: $x_c'(z)$ & $x_c(z)$

Correction of centroid misalignment



- Kick: $x_c'(z)$
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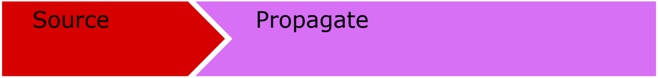
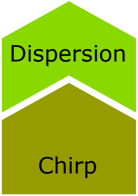
- Energy chirp $p \to z$

Correction of centroid misalignment



- Kick: $x_c'(z)$
- Propagate: $x_c'(z)$ & $x_c(z)$
- Energy chirp $p \to z$
- Dispersion $x \to z$



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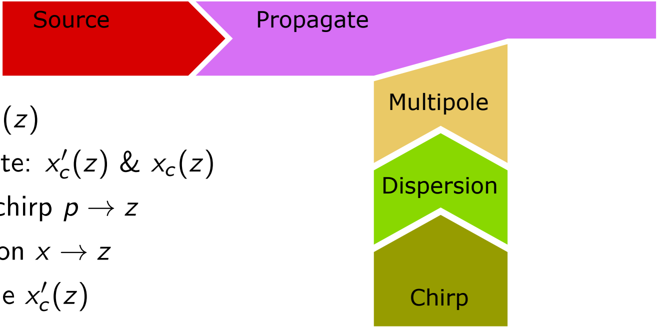
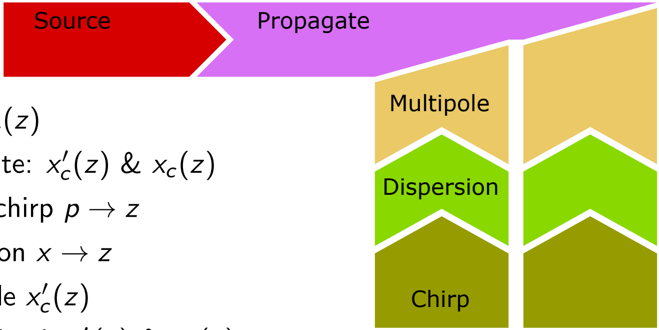
Correction of centroid misalignment



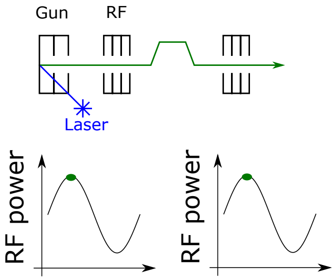
- Kick: $x_c'(z)$
- Propagate: $x_c'(z)$ & $x_c(z)$
- Energy chirp $p \rightarrow z$
- Dispersion $x \rightarrow z$
- Multipole $x_c'(z)$

Correction of centroid misalignment

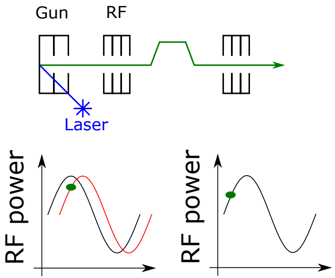


- Kick: $x_c'(z)$
- Propagate: $x_c'(z)$ & $x_c(z)$
- Energy chirp $p \to z$
- Dispersion $x \to z$
- Multipole $x_c'(z)$
- Second knob $x_c'(z)$ & $x_c(z)$

Energy induced orbit jitter

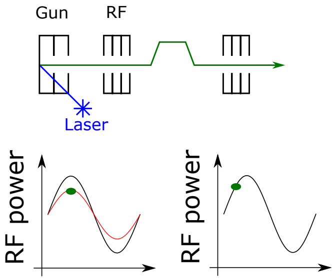


Energy induced orbit jitter



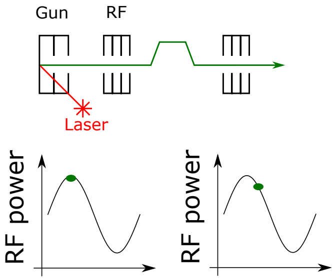
- Phase jitter
- Amplification trough BC

Energy induced orbit jitter



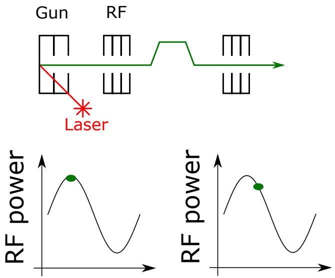
- Phase jitter
- Amplification trough BC
- Analogue for amplitude jitter

Energy induced orbit jitter



- Phase jitter
- Amplification trough BC
- Analogue for amplitude jitter
- Charge jitter leads to energy jitter

Energy induced orbit jitter



- Phase jitter
- Amplification trough BC
- Analogue for amplitude jitter
- Charge jitter leads to energy jitter

- Leaking dispersion from correction
- $R_{56} = \int_{BC} \frac{\eta}{\rho} ds$

Parametrization of beam tilt (χ)

$$\frac{x_c'(z)}{\sigma_{x'}} + \frac{x_c(z)}{\sigma_x} \cdot i = \sum_{n=0}^{\infty} \chi_n \left(\frac{z}{\sigma_z}\right)^n$$

- Taylor expansion of slice offset $x_c(z)$ and angle $x_c'(z)$
- Combine both series into complex values

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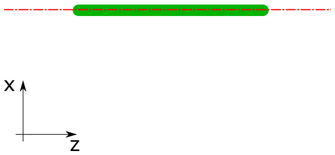
- Taylor expansion of slice offset $x_c(z)$ and angle $x_c'(z)$
- Combine both series into complex values
- Zero order
  - Orbit



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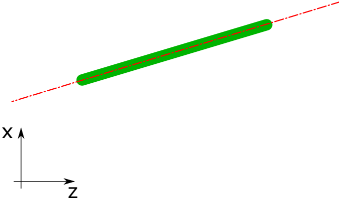
- Taylor expansion of slice offset $x_c(z)$ and angle $x_c'(z)$
- Combine both series into complex values
- Zero order
  - Orbit
- First order
  - Linear tilt



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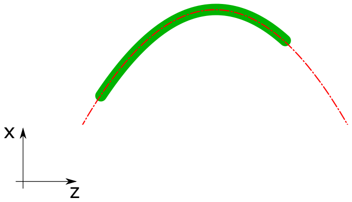
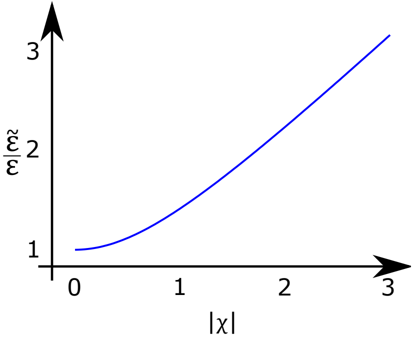
- Taylor expansion of slice offset $x_c(z)$ and angle $x_c'(z)$
- Combine both series into complex values
- Zero order
  - Orbit
- First order
  - Linear tilt
- Second order
  - Quadratic tilt

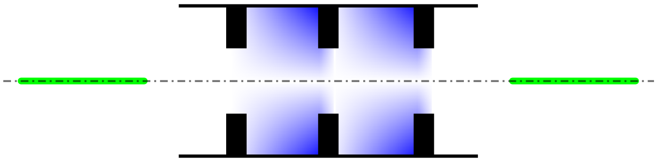


Optics perturbation through χ_1



- $\tilde{\varepsilon} = \varepsilon\sqrt{1 + |\chi_1|^2 \cdot (1+\alpha^2) + 2\alpha \cdot \sqrt{1+\alpha^2} \cdot \mathrm{Re}(\chi_1) \cdot \mathrm{Im}(\chi_1)}$
- $\alpha = 0 \rightarrow \tilde{\varepsilon} = \varepsilon \cdot \sqrt{1+|\chi_1|^2}$
- Influences optics

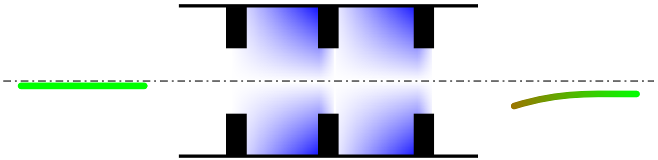
Source: Transverse wakefields



- $off = 0 \rightarrow V_x = 0$

$$V_x(s) = \int_{-\infty}^{s} W_x(s - s') \cdot off_x(s') \cdot \lambda(s') ds'$$

Source: Transverse wakefields



- $off = 0 \rightarrow V_x = 0$
- $off \neq 0 \rightarrow V_x \neq 0$

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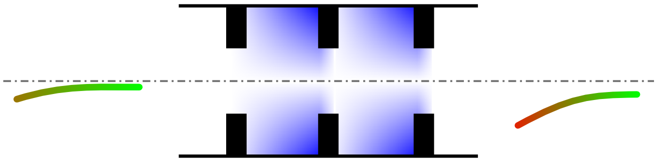
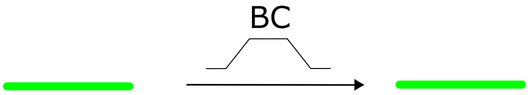


- $off = 0 \rightarrow V_x = 0$
- $off \neq 0 \rightarrow V_x \neq 0$
- Defocussing

$$V_x(s) = \int_{-\infty}^{s} W_x(s - s') \cdot off_x(s') \cdot \lambda(s') ds'$$

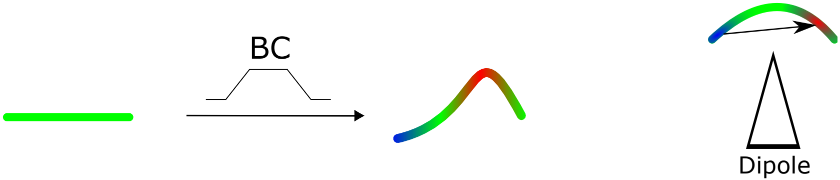
Source: Coherent Synchrotron Radiation



Incoherent Synchrotron Radiation

- Independent on current profile

Source: Coherent Synchrotron Radiation



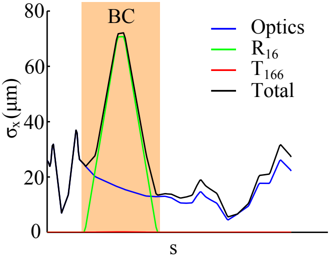
Incoherent Synchrotron Radiation

- Independent on current profile

Coherent Synchrotron Radiation

- Longitudinal dependent energy loss
- Dispersion varies effectively along bunch
- Transverse kick of recaptured synchrotron light

Beamsize along at the SITF

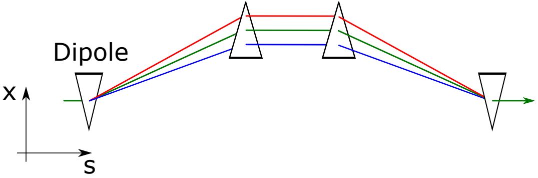


- Dominated by ${}^1\eta$ in the BC
- ${}^2\eta$ contribution is negligible

- Matched
- Normal (10x) compression
- Linear longitudinal phase space

Magnets in dispersive section

Ideal, zero length magnets



- ${}^1\eta_x / {}^1\eta_{x'} \sim 0$
- ${}^1\eta_y / {}^1\eta_{y'} \sim 0$
- ${}^2\eta_x / {}^2\eta_{x'} \sim 0$

Magnets in dispersive section

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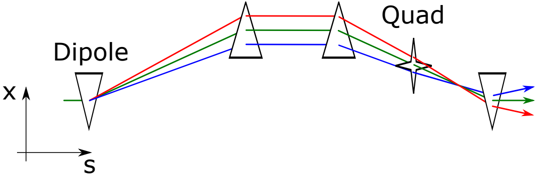
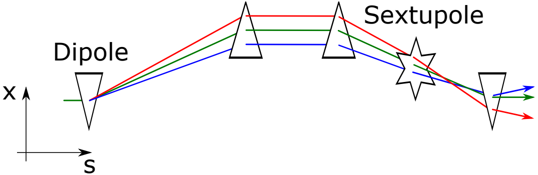


- $^{1}\eta_x / ^{1}\eta_{x'} \neq 0$
- $^{1}\eta_y / ^{1}\eta_{y'} \sim 0$
- $^{2}\eta_x / ^{2}\eta_{x'} \sim 0$

- Quadrupole magnet
  - $\Delta(^{1}\eta_x \cdot \delta) + \Delta x'_\beta = \frac{\eta_x \cdot \delta + x_\beta}{f}$
  - $\Delta\chi_1 = \frac{\eta}{f \cdot \sqrt{\varepsilon_x \cdot \gamma}} \cdot < \delta >$

Magnets in dispersive section

Ideal, zero length magnets



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- Sextupole magnet
  - $\Delta({}^2\eta'_x \cdot \delta^2) + \Delta\xi'_x + \mathcal{O}(x_\beta^2 + y_\beta^2) = \frac{y_\beta^2 - ({}^1\eta_x \cdot \delta + x_\beta)^2}{m}$

Magnets in dispersive section

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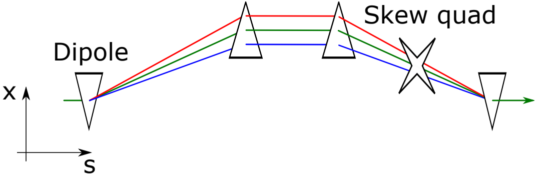

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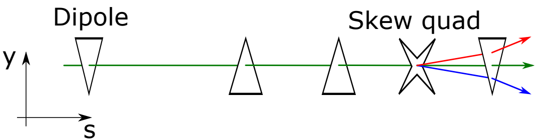
- Skew quadrupole magnet
  - Analogue

Magnets in dispersive section

Ideal, zero length magnets



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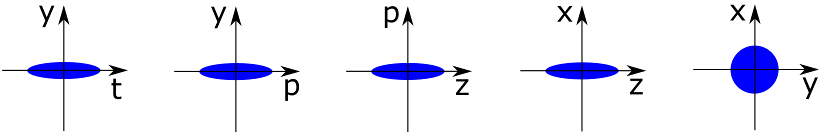
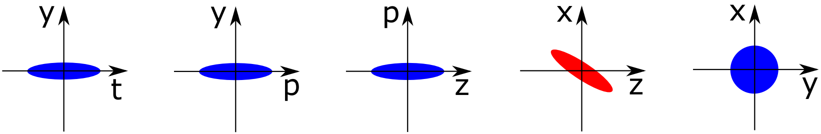
Streak



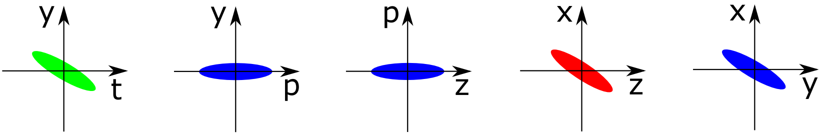
- Operator can only observe $x - y$

Streak



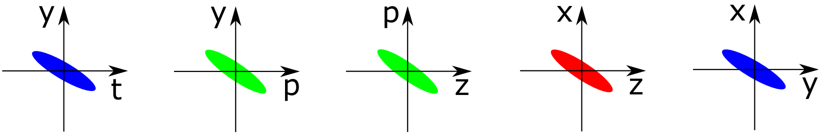
- Operator can only observe $x - y$
- $x - z$ is not measurable

Streak



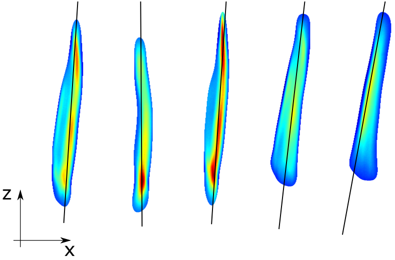
- Operator can only observe $x - y$
- $x - z$ is not measurable
- Accelerate in y with RF

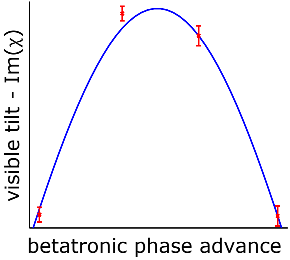
Streak



- Operator can only observe $x - y$
- $x - z$ is not measurable
- Accelerate in y with RF
- Use longitudinal energy dependence combined with dispersion

Method to measure χ

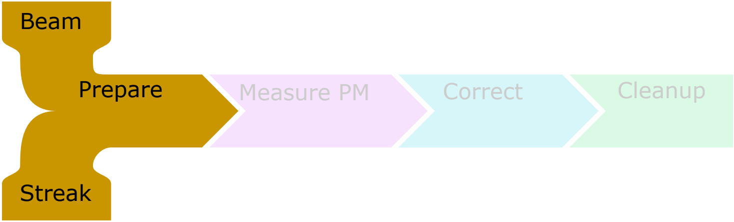




- Streak
- Scan phase advance
- Normalize
- Correlate
- Reconstruct at one point

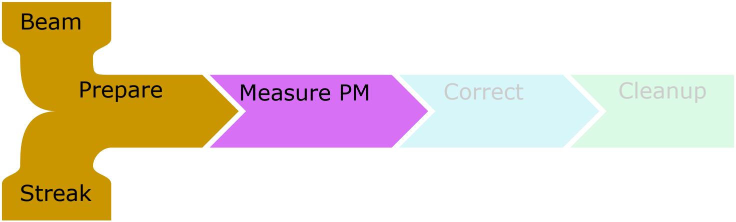
$$\frac{x_c'(z)}{\sigma_{x'}} + \frac{x_c(z)}{\sigma_x} \cdot i = \sum_{n=0}^{\infty} \chi_n \left(\frac{z}{\sigma_z}\right)^n$$

Algorithm



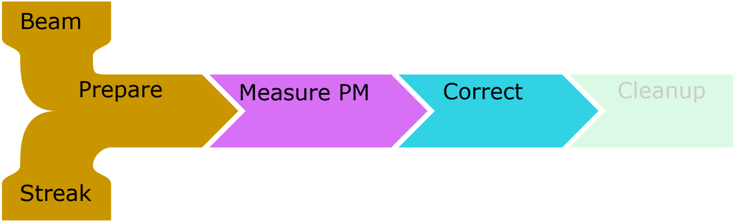
- Measure
  - Optics
  - Momentum
  - $< \delta >$
- Streak
  - Minimize mismatch

Algorithm



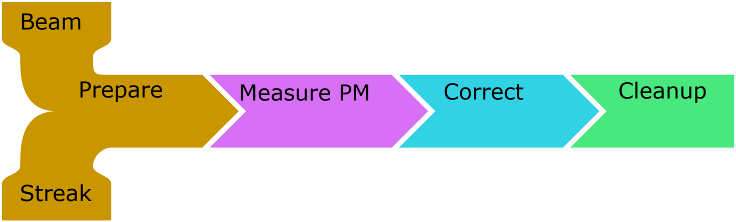
- Knobs in the bunch compressor
  - Quadrupole
  - Sextupole
  - Skew quadrupole
- Penalty for several phase advances
  - 1. & 2. order $x - z$ correlation
  - Chromaticity
- Correct mismatch

Algorithm



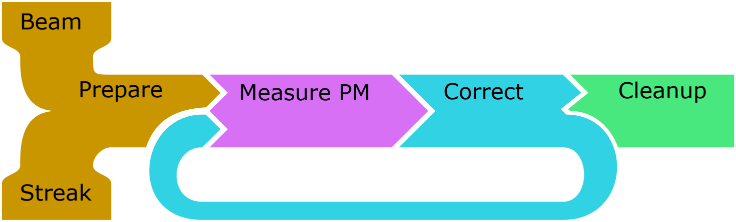
- Use pseudo inverse
- Apply changes

Algorithm



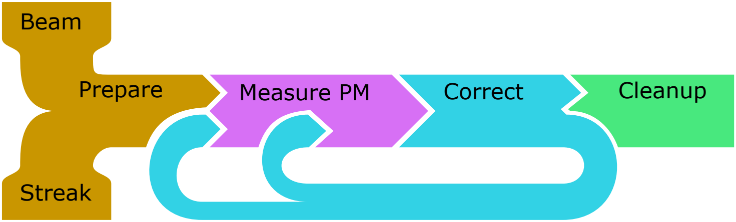
- Remove streak
- Rematch
- Check compression

Algorithm



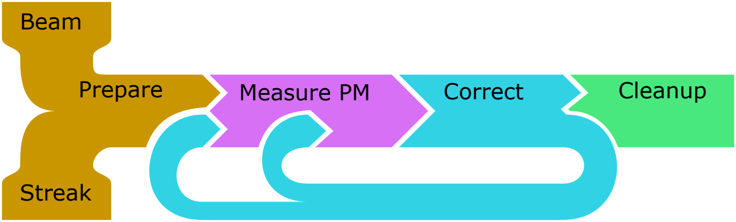
- Iterate process

Algorithm



- Iterate process
- Reuse perturbation matrix

Algorithm



- Iterate process
- Reuse perturbation matrix
- Very robust
    - Optics mismatch
    - Machine drifts

GUI

When:	Tue 30-Jul-13 19:21
Author:	CSR
Entry:	Measurement
System:	MATLAB
Title:	KillCSR

Finished run after 414 s.
build 24.7.3

Magnets

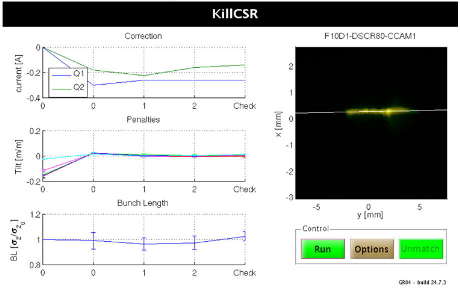
Name	Current [A]
F10BC-MQUA10	-2.64e-01
F10BC-MQUA20	-1.40e-01
F10BC-MSQU10	0.00e+00
F10BC-MSQU20	0.00e+00

Penalties

Index	Initial	Final
1	-1.61e-01 ± 1.66e-02	-7.07e-03 ± 5.02e-03
2	-1.52e-01 ± 1.92e-02	5.58e-03 ± 5.06e-03
3	-1.60e-01 ± 1.46e-02	8.03e-04 ± 4.72e-03
4	-1.18e-01 ± 8.95e-03	1.88e-03 ± 2.15e-03
5	-2.77e-02 ± 1.85e-03	8.74e-03 ± 3.40e-03
Bunch length	1.00e+00 ± 0.00e+00	1.02e+00 ± 3.89e-02

Options

Option	Value
Mode	QTDCx
E (MeV)	180.00
Matching	0.00
#PM	3.00
Streak	2.70
Stepsize	0.04
Stepreduction	1.50
Reuse PM	1.00
Start@0	1.00
Cycle	0.00
No artifact	1.00
#Pictures	10.00
Noisecut	0.30
Threshold	0.20



This figure can be accessed here: /afs/psi.ch/intranet/FIN/Data/FIN250-Phase3X/2013-07-30/KillCSR2013.07.30-19.14._Figure001.fig

Raw data can be found here: /afs/psi.ch/intranet/FIN/Data/FIN250-Phase3X/2013-07-30/KillCSR2013.07.30-19.14.26*

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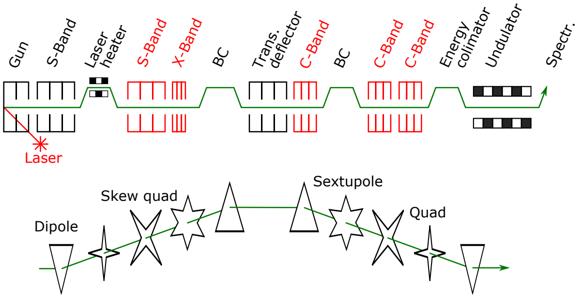
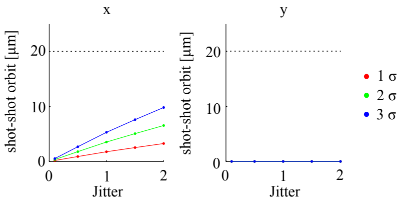
Setup for sensitivity study



Monte Carlo simulations for combined jitter sources

- Charge ($\sigma_Q/Q = 0.1$)
- RF phase ($\sigma_\phi = 0.05°$)
- RF amplitude ($\sigma_A/A = 0.0018$)

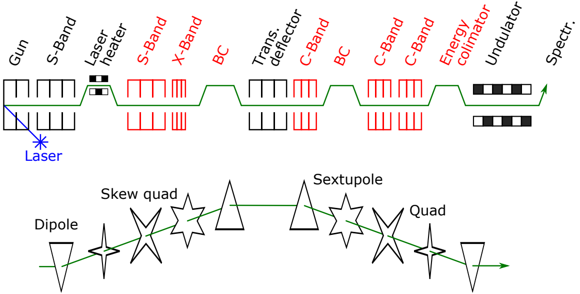
RF and laser stability



Simulations for SwissFEL

- Orbit jitter low
- Bunch length jitter negligible
- Current profile jitter negligible

Setup of SwissFEL



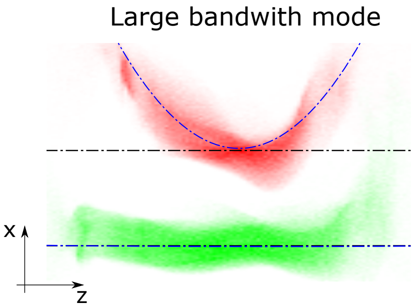
Tilt sources

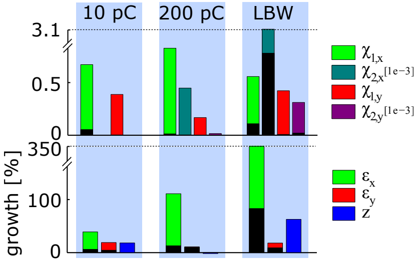
- CSR (3 Stages)
- Wakefields (X- & C-Band)

Knobs in BC1 & BC2

- 2x2 Quadrupole
- 2x2 Skew quadrupole
- 2x2 Sextupole

Simulation results

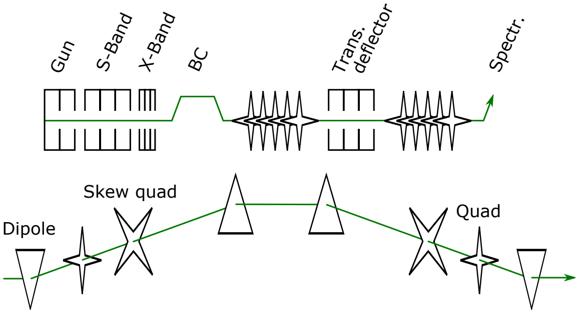




Simulations using elegant

- Clear reduction for all cases
- Higher order modes still uncorrected

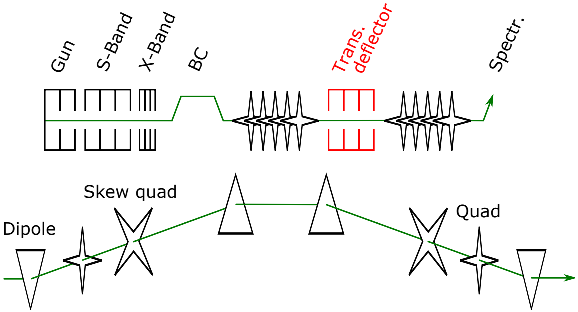
Setup of SwissFEL Injector Test Facility



Key features

- Moveable bunch compressor
- Moveable X-Band cavity

Setup of SwissFEL Injector Test Facility



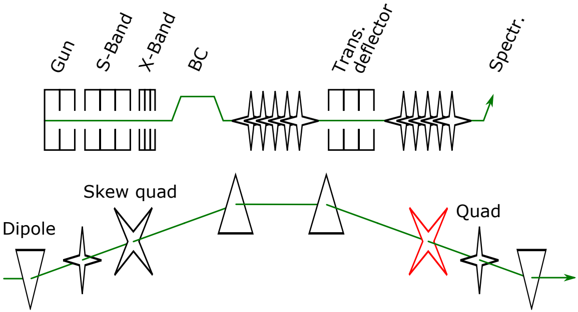
Key features

- Moveable bunch compressor
- Moveable X-Band cavity

Streaking

- Transverse deflection cavity

Setup of SwissFEL Injector Test Facility



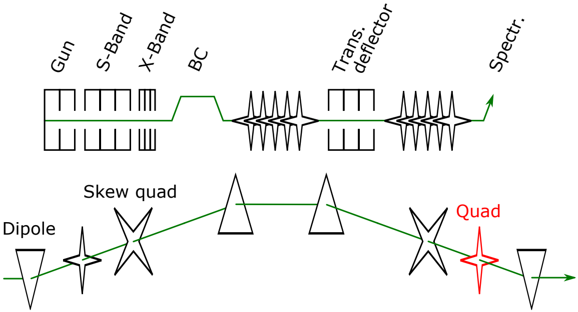
Key features

- Moveable bunch compressor
- Moveable X-Band cavity

Streaking

- Transverse deflection cavity
- Skew quadrupole within BC

Setup of SwissFEL Injector Test Facility



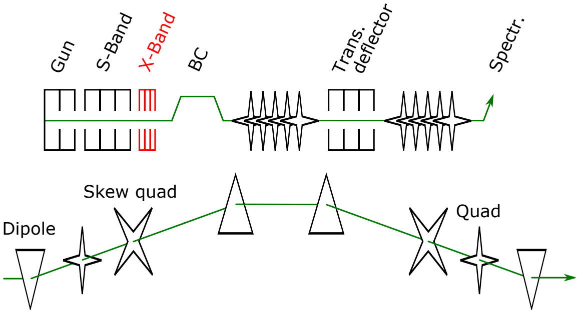
Key features

- Moveable bunch compressor
- Moveable X-Band cavity

Streaking

- Transverse deflection cavity
- Skew quadrupole within BC
- Quadrupole within BC

Setup of SwissFEL Injector Test Facility



Key features

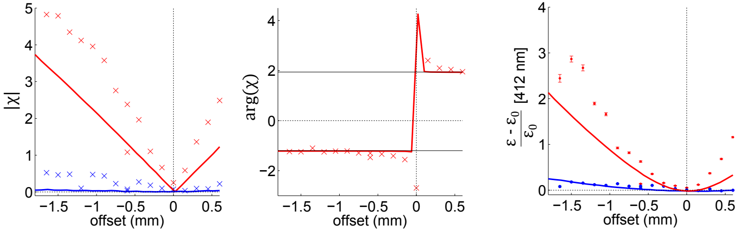
- Moveable bunch compressor
- Moveable X-Band cavity

Streaking

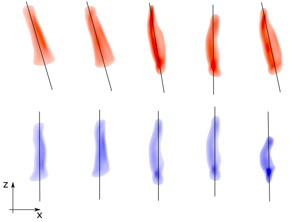
- Transverse deflection cavity
- Skew quadrupole within BC
- Quadrupole within BC

Measurement results

	Original	Corrected
Measurement	× (red)	× (blue)
Simulation	— (red)	— (blue)



- Reduction for all phase advances
- Significant reduction of ε
- Significant reduction of χ



Summary

- Introduction of χ
- Very robust tilt correction procedure
- Relevant reduction of χ and ε
- Works simultaneously in both transversal planes

Thank you for your attention

My special thanks to

- Sven Reiche
- Bolko Beutner
- Eduard Prat
- Masamitsu Aiba
- Simona Bettoni

- Hans Braun
- Marco Pedrozzi
- Thomas Schietinger

- All technical groups involved at the SITF

Optics with χ

For $\chi = \chi_0 + \chi_1$

- Beam size
  - $\tilde{\sigma}_x = \sigma_x \sqrt{1 + \mathrm{Im}(\chi_1)^2}$
  - $\tilde{\sigma}_{x'} = \sigma_{x'} \sqrt{1 + \mathrm{Re}(\chi_1)^2}$
  - $\tilde{\varepsilon} = \varepsilon \sqrt{1 + |\chi_1|^2 \cdot (1 + \alpha^2) + 2\alpha \cdot \sqrt{1 + \alpha^2} \cdot \mathrm{Re}(\chi_1) \cdot \mathrm{Im}(\chi_1)}$
- Optics
  - $\tilde{\alpha} = \frac{\varepsilon}{\tilde{\varepsilon}} \left(\alpha - \sqrt{1 + \alpha^2} \cdot \mathrm{Re}(\chi_1) \cdot \mathrm{Im}(\chi_1) \right)$
  - $\tilde{\beta} = \beta \sqrt{\frac{1 + \tilde{\alpha}}{1 + \alpha} \cdot \frac{1 + \mathrm{Im}(\chi_1)^2}{1 + \mathrm{Re}(\chi_1)^2}}$
  - $\tilde{\gamma} = \gamma \sqrt{\frac{1 + \tilde{\alpha}}{1 + \alpha} \cdot \frac{1 + \mathrm{Re}(\chi_1)^2}{1 + \mathrm{Im}(\chi_1)^2}}$
- Transfer for frozen longitudinal phase space
  - $\begin{pmatrix} \mathrm{Im}(\chi_1) \\ \mathrm{Re}(\chi_1) \end{pmatrix} = \left(\sqrt{\beta_0} \sqrt{\gamma_0} \right) \otimes \begin{pmatrix} \sqrt{\frac{1}{\beta}} \\ \sqrt{\frac{1}{\gamma}} \end{pmatrix} \circ R \cdot \begin{pmatrix} \mathrm{Im}(\chi_{1,0}) \\ \mathrm{Re}(\chi_{1,0}) \end{pmatrix}$

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- M. Borland, “elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation”, Advanced Photon Source LS-287, 2000.
- D. Edwards, “An Introduction to the Physics of High Energy Accelerators”, Wiley-vch, 2004.