PAUL SCHERRER INSTITUT

+ SwissFEL

# Low slice emittance preservation during bunch compression


S. Bettoni
M. Aiba, B. Beutner, M. Pedrozzi, E. Prat, S. Reiche, T. Schietinger

simona.bettoni@psi.ch

# Outline



1. **Introduction**
2. **Experimental studies**
   a. Measurement procedure
   b. Characterization of the core emittance increase
   c. Systematic checks
3. **Simulations**
   a. Simulations scenarios
   b. Characterization of the core emittance blow-up
4. **Discussion**
5. **Conclusions**

# Introduction: in other machines

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FLASH
Free-electron laser FLASH

Proceedings of EPAC 2006, Edinburgh, Scotland MOPCH013

**SLICE EMITTANCE MEASUREMENTS AT FLASH**

Michael Röhrs*, Christopher Gerth, Markus Hüning, Holger Schlarb
Deutsches Elektronen-Synchrotron DESY, D-22603 Hamburg, Germany

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 18, 050702 (2015)

**Measurements and analysis of a high-brightness electron beam collimated in a magnetic bunch compressor**

F. Zhou,* K. Bane, Y. Ding, Z. Huang, H. Loos, and T. Raubenheimer
*SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, California 94025, USA*
(Received 5 March 2015; published 18 May 2015)

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 16, 042801 (2013)

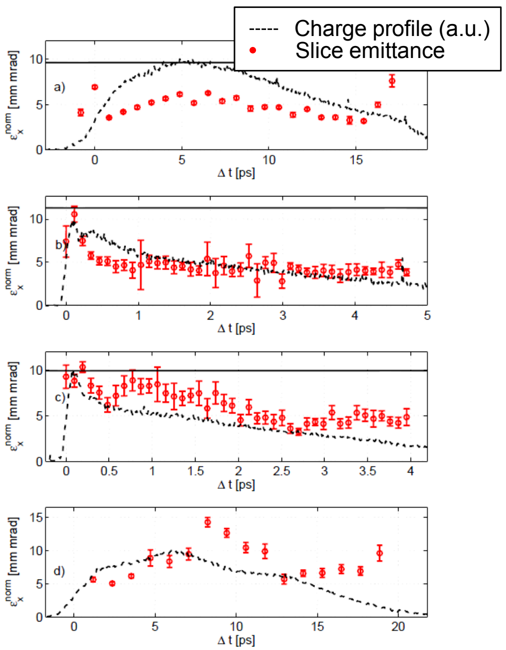
**Electron slicing for the generation of tunable femtosecond soft x-ray pulses from a free electron laser and slice diagnostics**

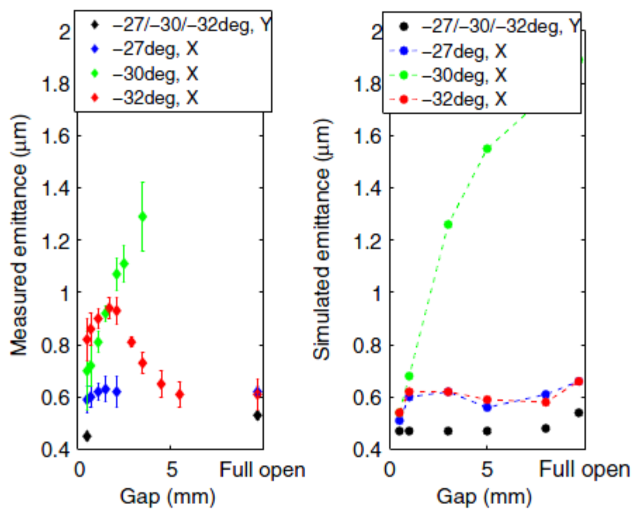
S. Di Mitri, D. Castronovo, I. Cudin, and L. Fröhlich
*Elettra-Sincrotrone Trieste S.C.p.A., 34149 Basovizza, Trieste, Italy*
(Received 3 October 2012; published 4 April 2013)

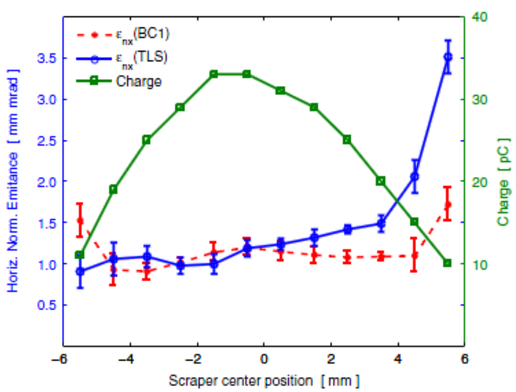
1 < Compression factor ≤ 5

Compression factor ~ 4.5

Compression factor = 5.5




Slice emittance increase

Slice emittance increase

No slice emittance increase

# SwissFEL: FEL in Switzerland

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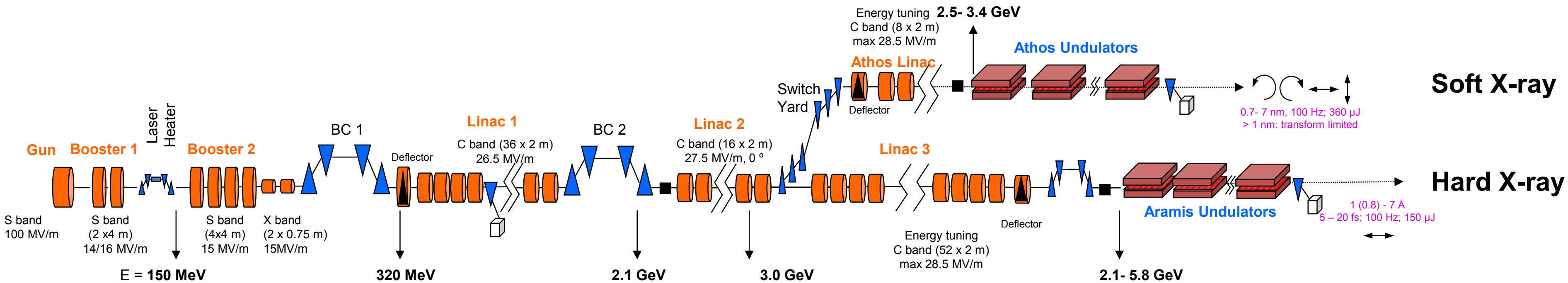
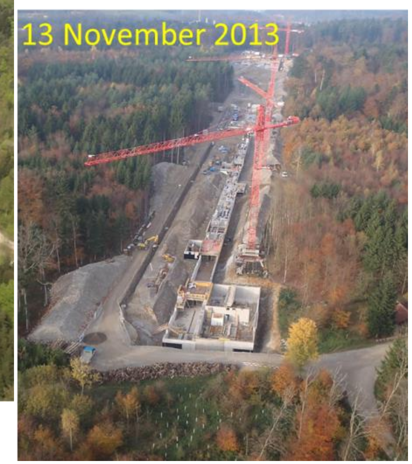



| | |
|---|---|
| **Wavelength** | 1 - 70 Å |
| **Pulse duration** | 3 – 20 fs |
| **Maximum e- beam energy** | 5.8 GeV |
| **e- beam charge** | 10 – 200 pC |
| **Repetition rate** | 100 Hz |
| **Slice emittance (expected performances)** | 200 nm (10 pC)<br>300 nm (200 pC) |
| **Slice energy spread** | 250-350 keV |
| **Saturation length** | < 50 m |


Pictures courtesy of I. Widmer





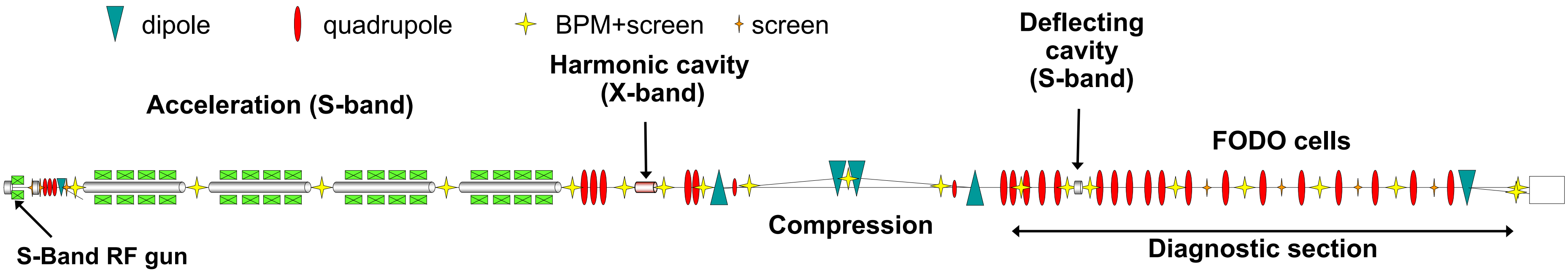

- ❑ **Construction started in 2013**
- ❑ **Commissioning planned in Feb 2016**
- ❑ **Aramis user operation planned in Dec 2017**
- ❑ **Athos user operation planned in 2021**

# SwissFEL Injector Test Facility (SITF)



## Missions

- Benchmark the simulation expectations and prove the feasibility of SwissFEL
- Develop and test components/systems and optimization procedures in SwissFEL




## Commissioning phases

| | | |
|---|---|---|
| **Max e- beam charge** | 200 pC | |
| **Laser longitudinal shape** | Flat-top | Gaussian |
| **Laser longitudinal length** | 9.9 ps FWHM | 3.7 ps RMS |
| **Laser transverse shape** | Cut Gaussian | |
| **Laser transverse RMS** | 0.18 mm | |
| **Max e- beam energy** | 266 MeV | |
| **Repetition rate** | 100 Hz | |

**Phase 1:** Electron source and diagnostics (2010)

**Phase 2:** Phase 1 + (some) S-band accelerations (2010-2011)

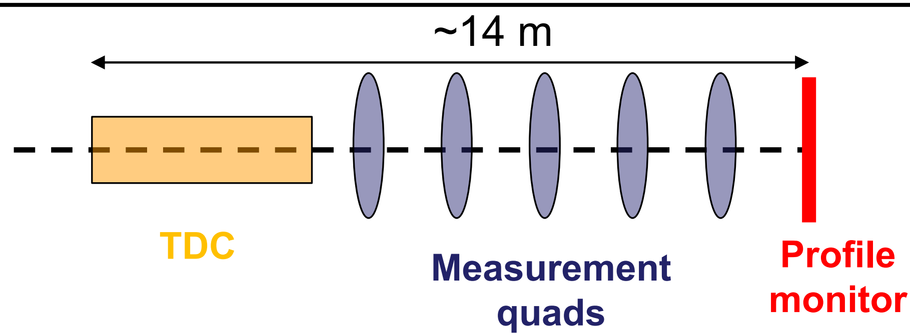
**Phase 3:** Machine in full configuration: all RF structures operational and bunch compressor installed (2012-2013)

**Phase 4:** Undulator installed for several weeks (2014)

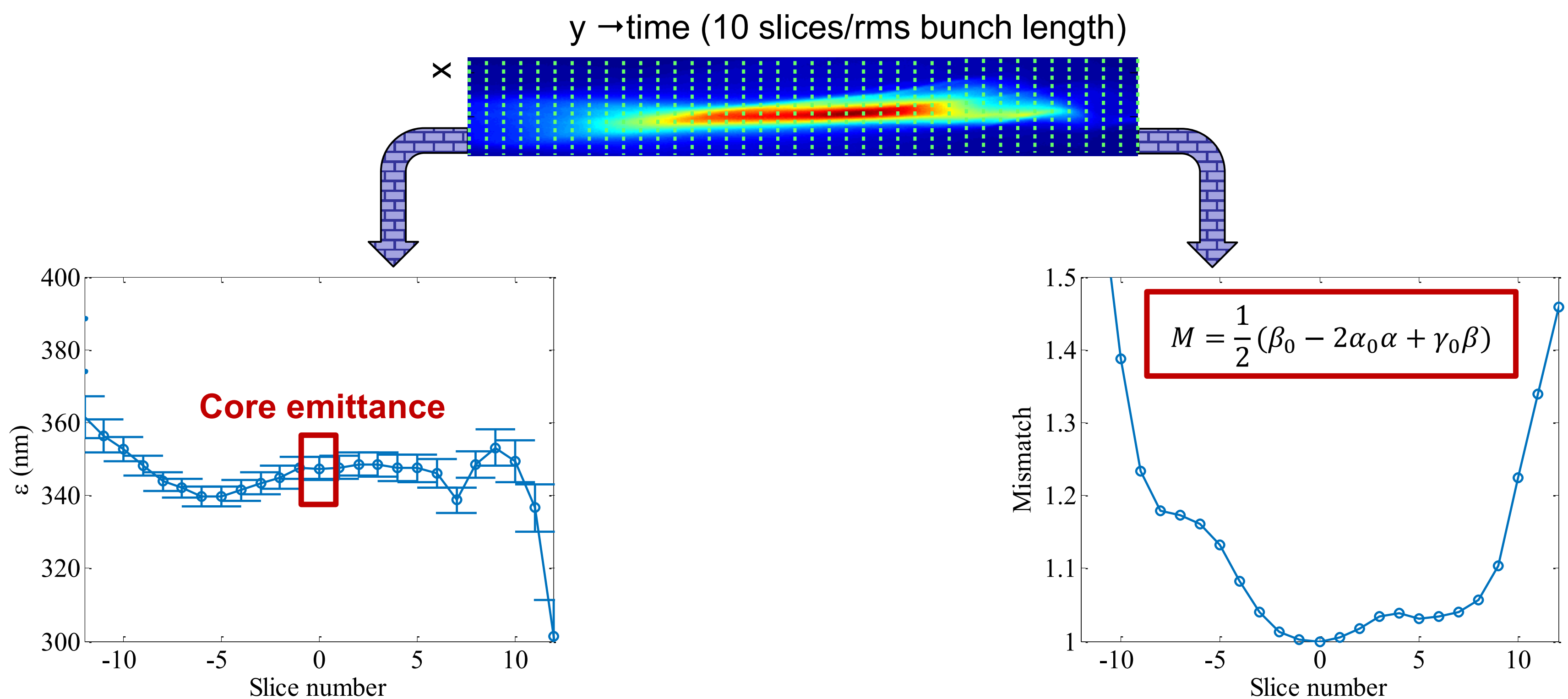
**Phase 4+:** PSI gun installed (Oct 2014)

# Slice emittance measurement






- 35 m <βx< 40 m, βy<10 m at the PM
- Phase advance in y ~270 °
- Phase advance in x from 0 to ~180°



# Measurements: compression factor

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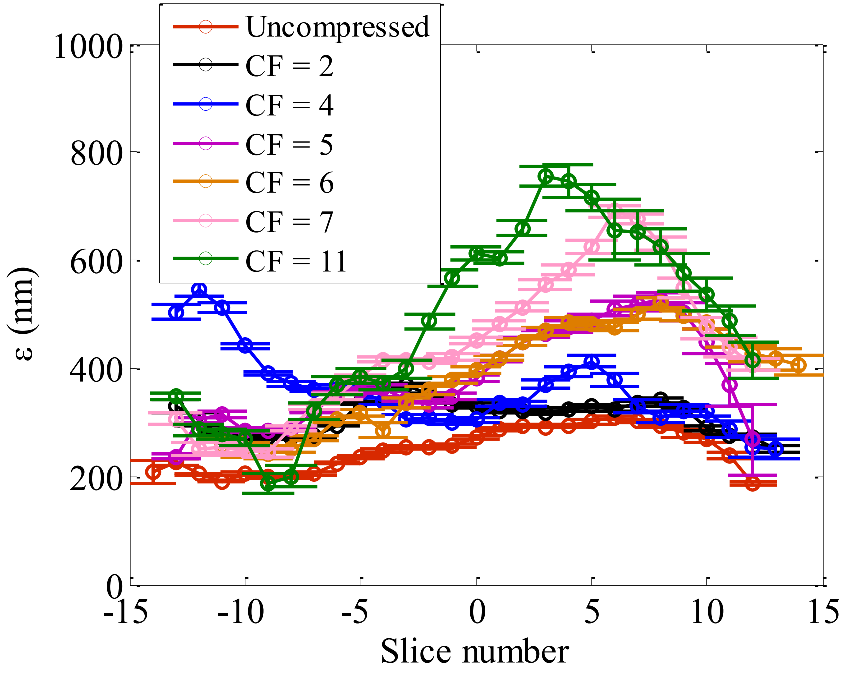
The bunch compression factor, CF, is given by:

$$CF = \frac{1}{1 - hR_{56}}$$

h: relative longitudinal chirp
$R_{56}$: derivative of the path length on energy



# Measurements: compression factor



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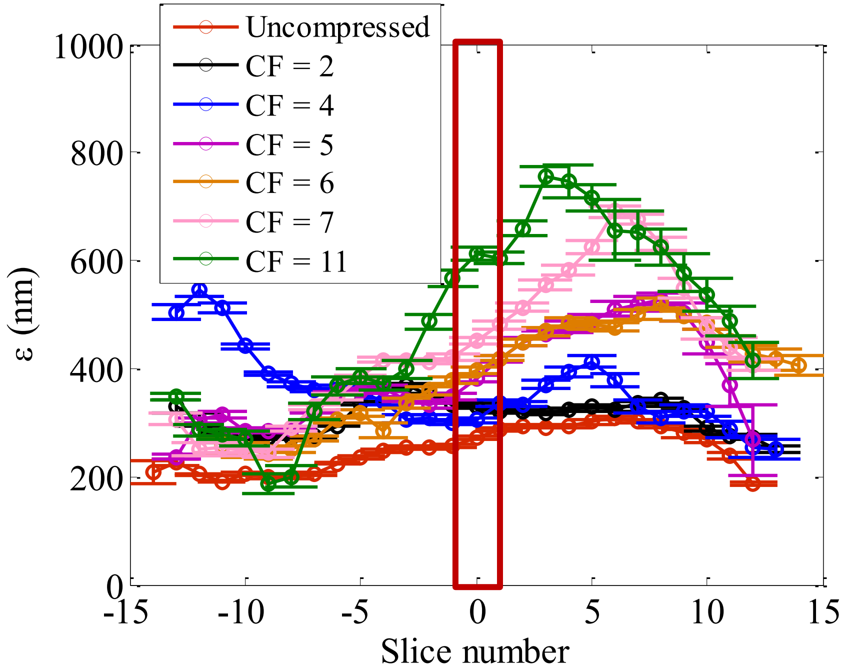
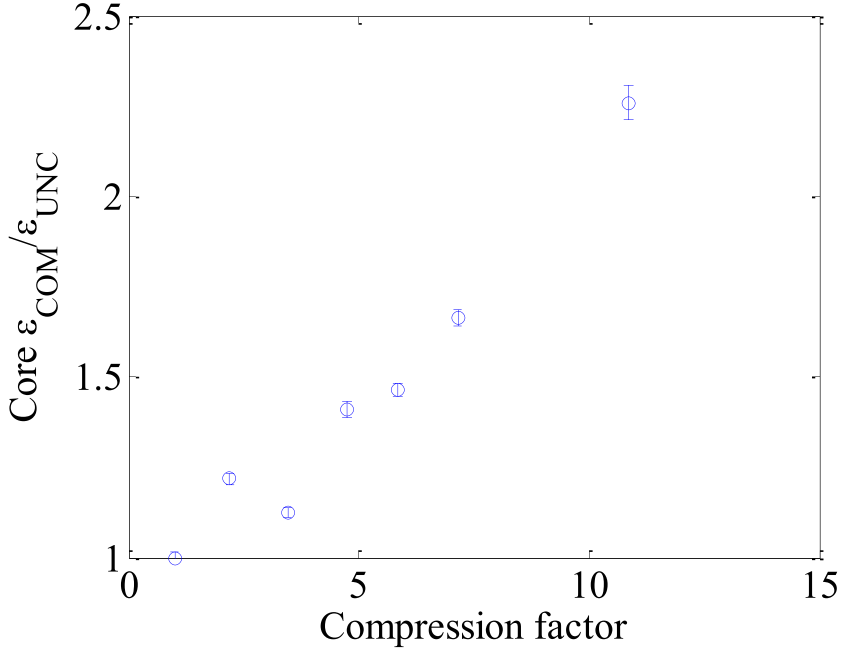


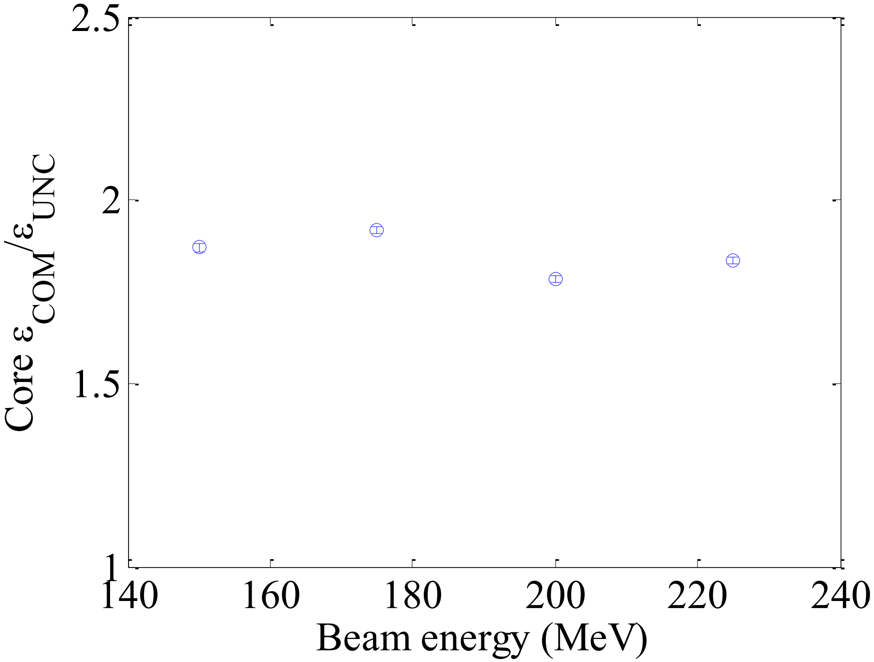

Core emittance increases versus CF

# Measurements: other parameters

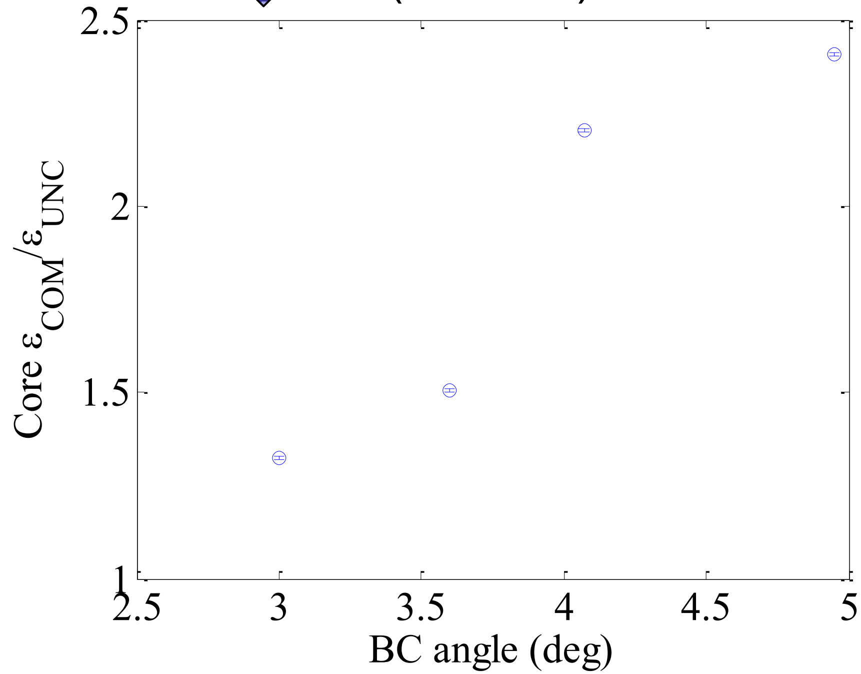


$$CF = \frac{1}{1 - hR_{56}}$$

Scan over E
(CF < 10)




Scan over $R_{56}$
(CF < 10)

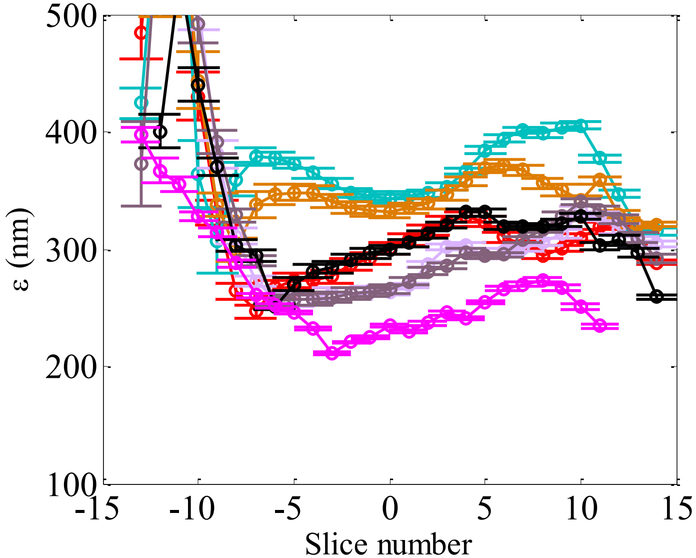


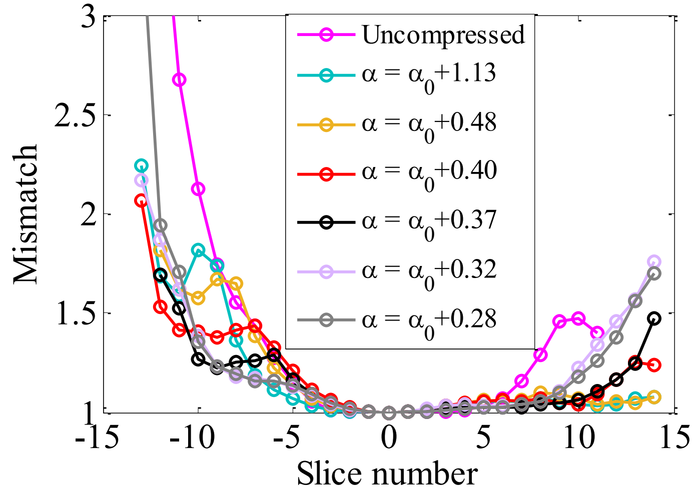

- ❑ Core emittance increase does not depend on the beam energy
- ❑ Core emittance increase is smaller for smaller BC bending angles

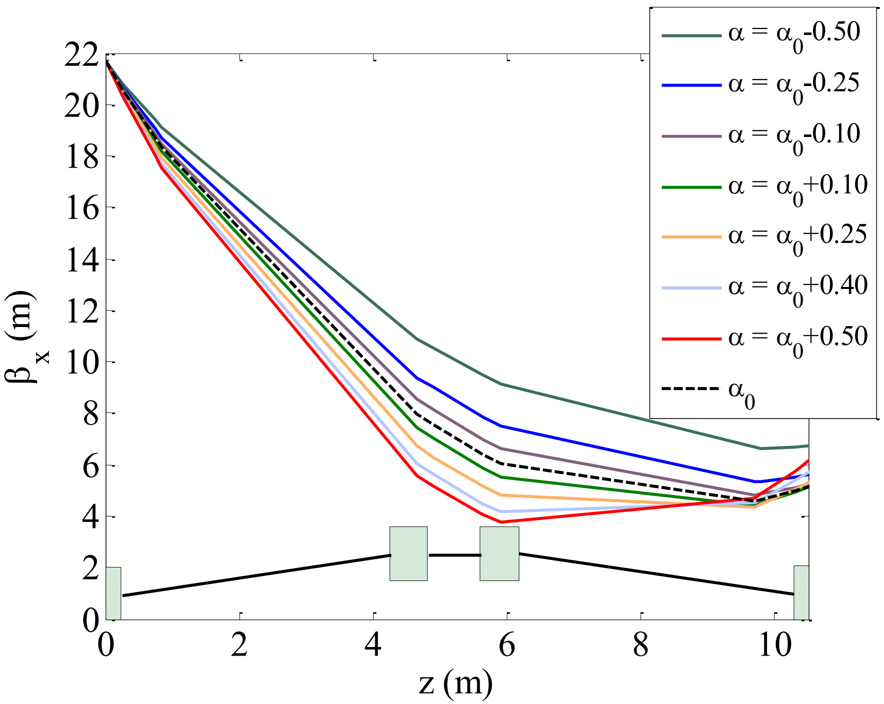
# Measurements: optics dependence



At constant CF (<10) we varied the optics along the bunch compressor



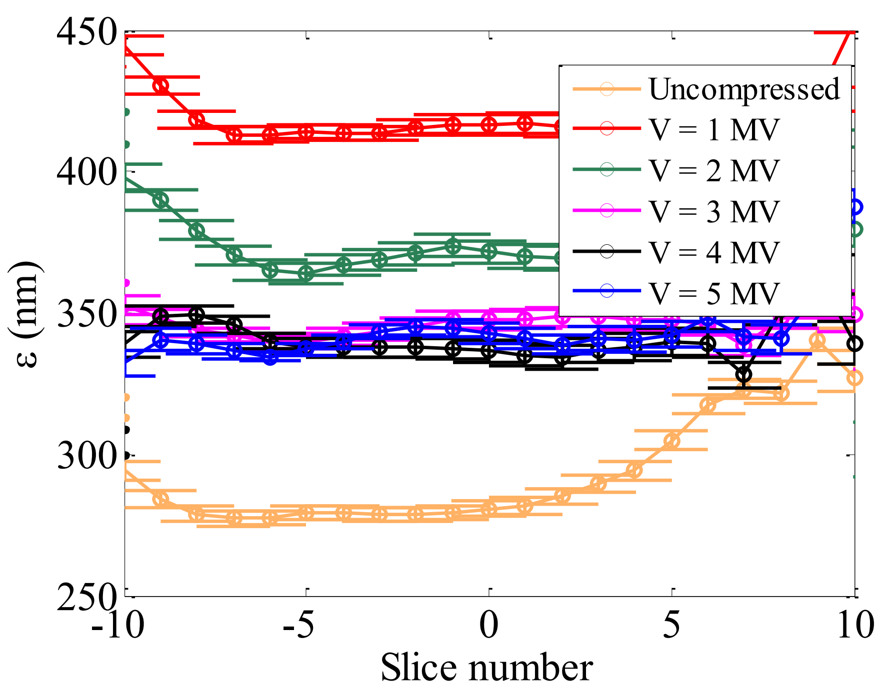

- ❑ High sensitivity of the core emittance increase on the optics along BC
- ❑ Smaller emittance blow-up for $\alpha \sim \alpha_0+0.3$, corresponding to the optics with the small $\beta_x$ at the two last dipoles

# Systematic checks

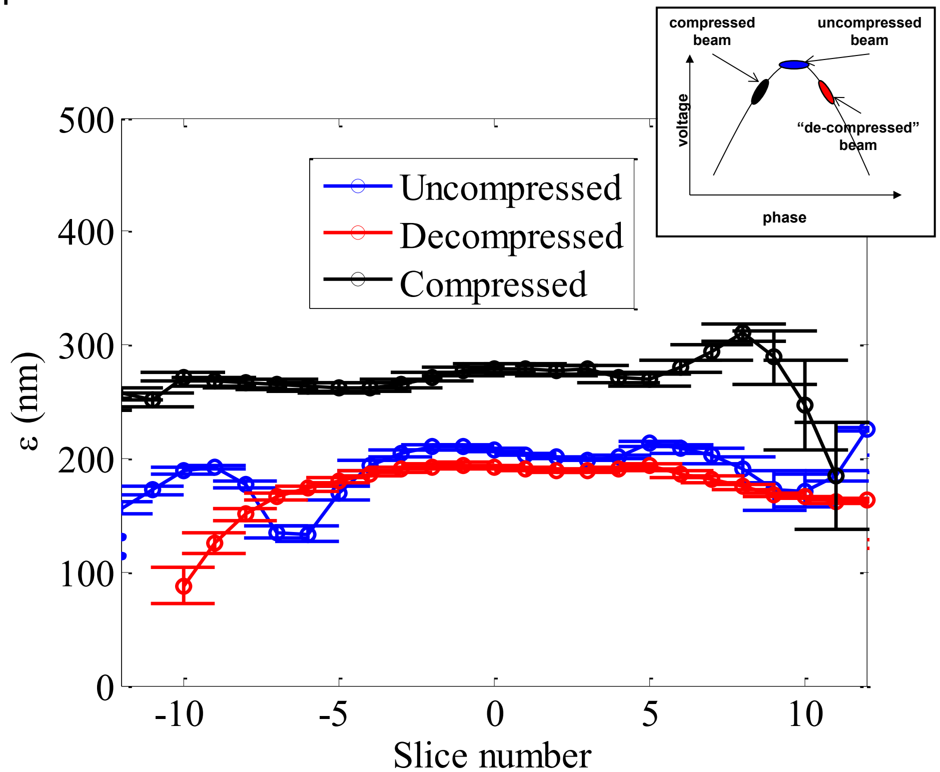


Before proceeding we answered to these questions:

- ❑ Are the measurements resolution limited?
- ❑ The slice energy spread increases with the compression factor: are spurious dispersion and chromaticity along the single slice increasing the core emittance?
- ❑ Tilt in the (s,x) plane: ~10% emittance blow-up




Slice emittance does not depend on the TDC voltage (V>3 MV)




Uncompressed and *decompressed* bunch have similar slice emittances

simona.bettoni@psi.ch

# Simulations scenarios

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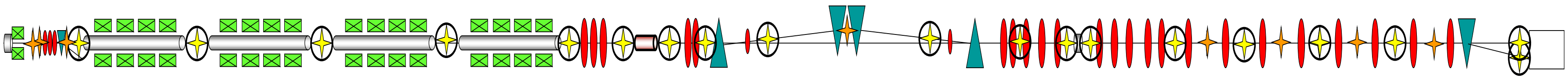


1 — Astra | Elegant

2 — Astra | Elegant | CSRTrack | Elegant

**ASTRA**

Author: Klaus Floettmann
DESY

A Space Charge Tracking Algorithm
Version 3.0
October 2011
(Update April 2014)

- 3D space charge forces
- No CSR

User's Manual for elegant

Program Version 28.1.0
Advanced Photon Source
Michael Borland

July 24, 2015

- 1D space charge forces
- 1D CSR

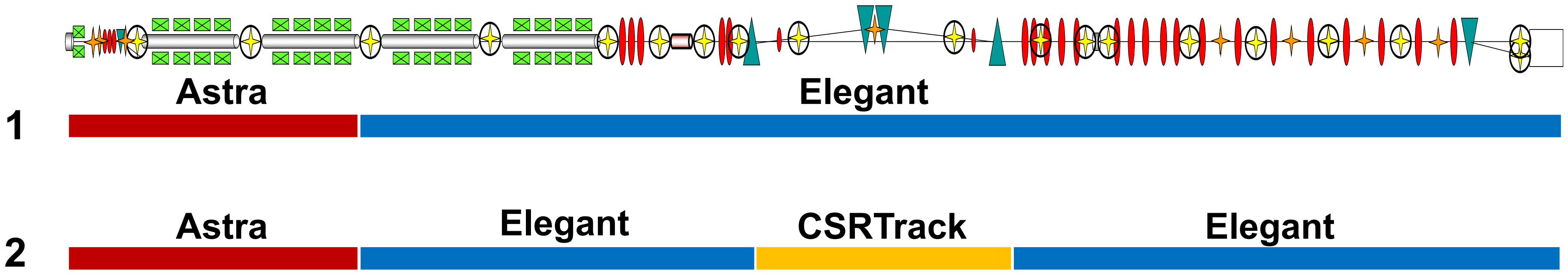
CSRtrack: FASTER CALCULATION OF 3-D CSR EFFECTS

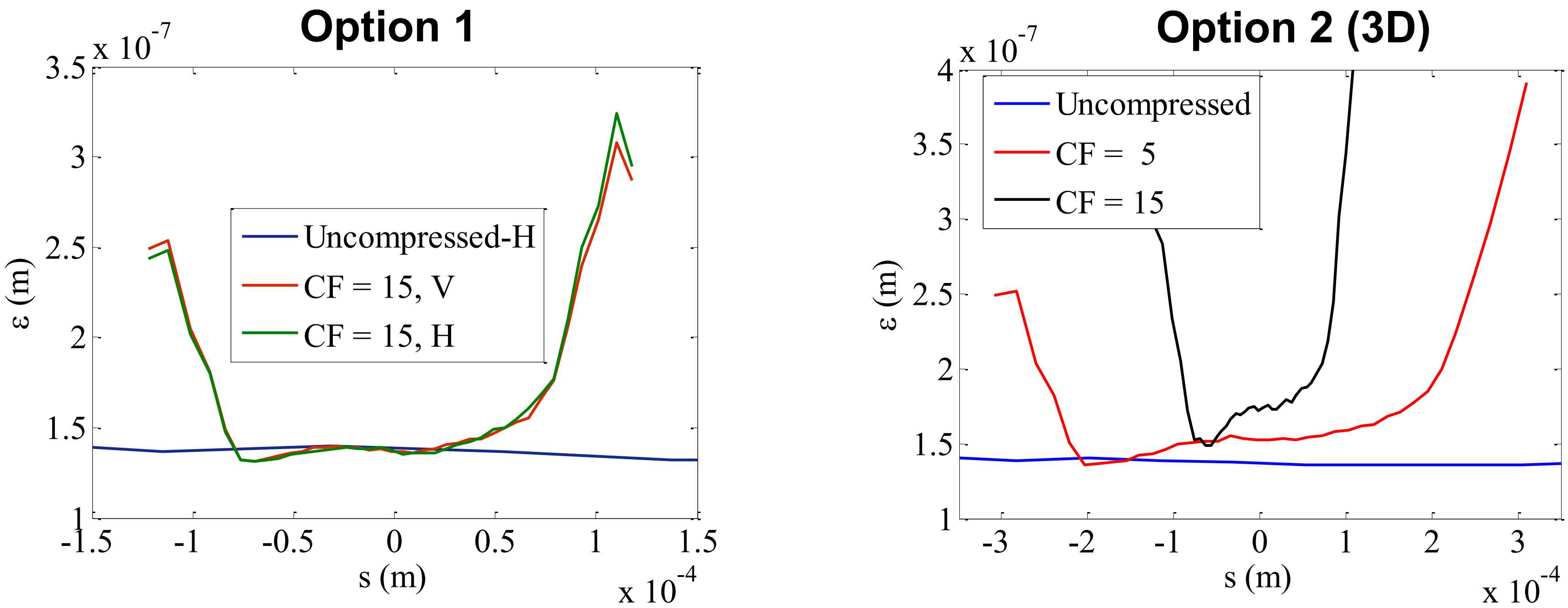
M. Dohlus, T. Limberg, DESY, Hamburg, Germany

- 3D space charge forces
- 3D CSR

# 1D versus 3D





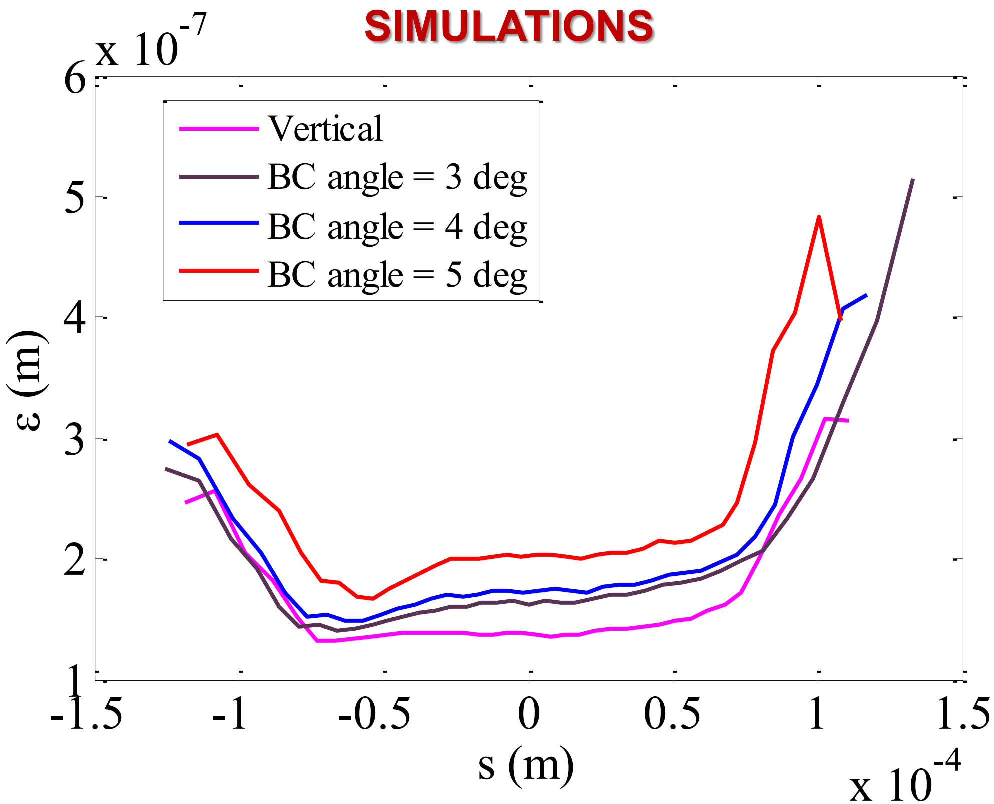

- Not observed core emittance increase for the option 1
- Observed core emittance increase versus CF using 3D version of CSRTrack
- In the following vertical emittance equivalent to horizontal uncompressed and CF = 15

# Dependence on BC angle

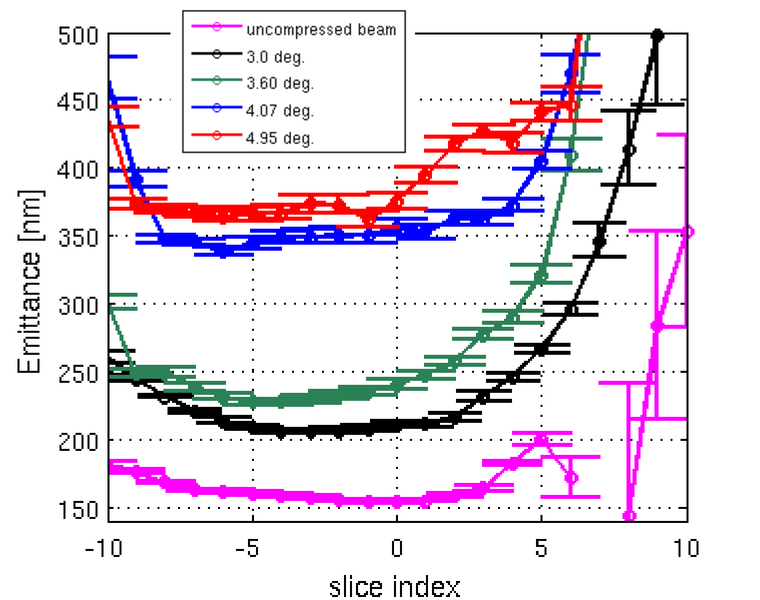


Simulated at constant CF the dependency of the slice emittance versus the BC bending angle

**SIMULATIONS**




**MEASUREMENTS**



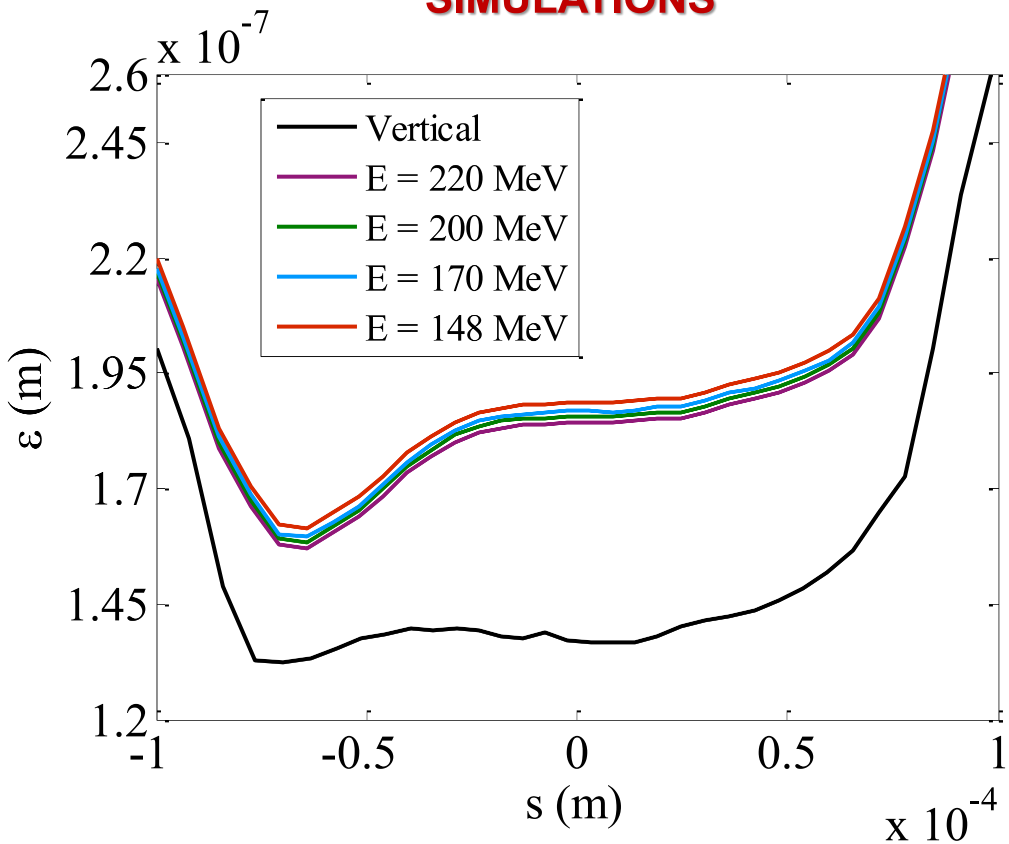

Core emittance increase is smaller for a smaller BC bending angle

simona.bettoni@psi.ch

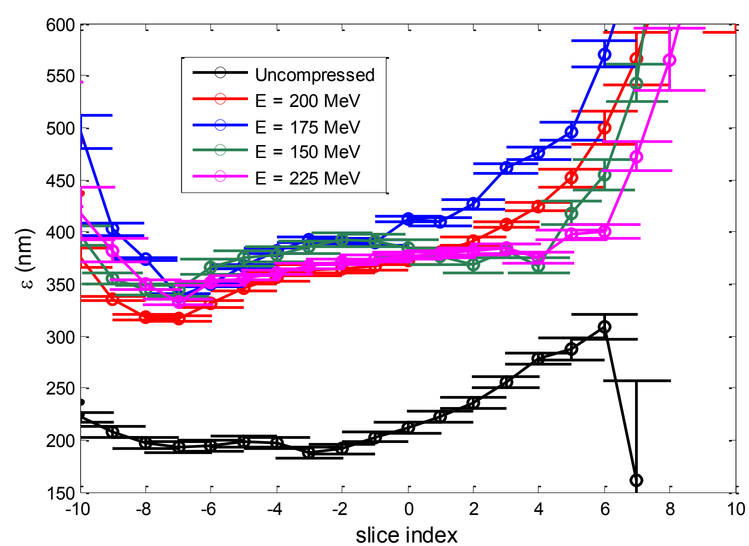
# Dependence on beam energy

Simulated at constant CF the dependency of the slice emittance versus the beam energy

**SIMULATIONS**



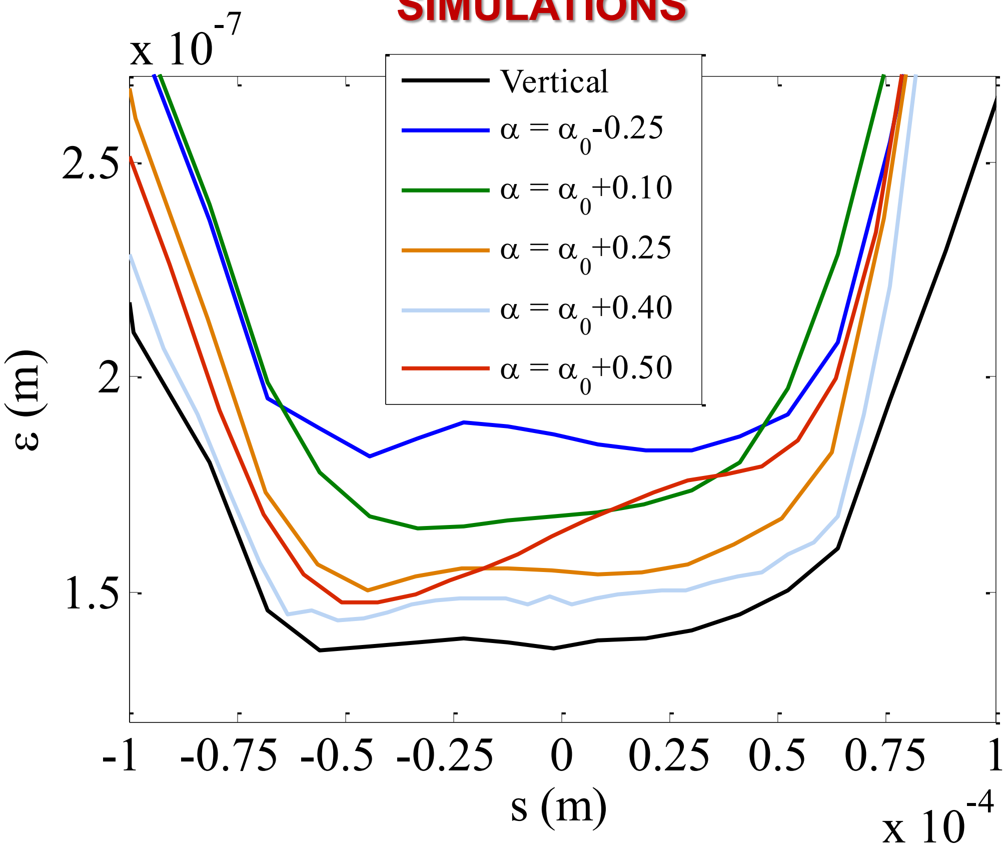

**MEASUREMENTS**

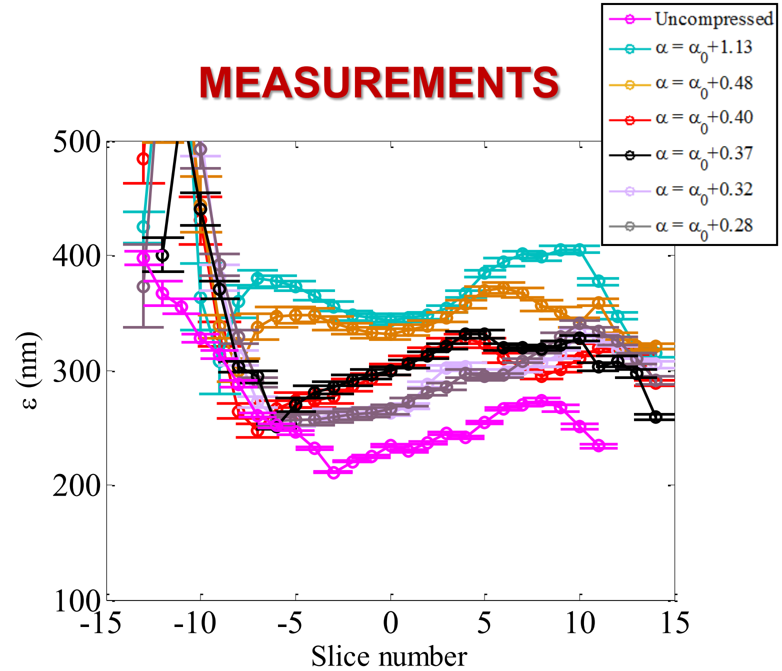



Core emittance increase does not dramatically depend on the beam energy

# Dependence on optics along BC

Varied the optics along BC at constant compression factor



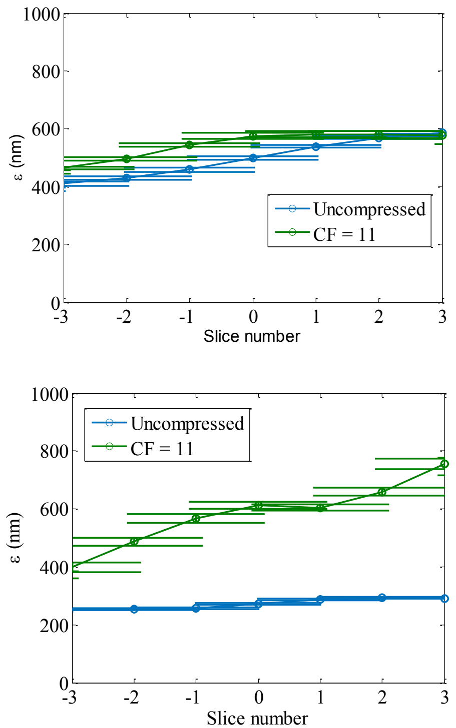

Qualitative agreement

# Dependence on incoming emittance

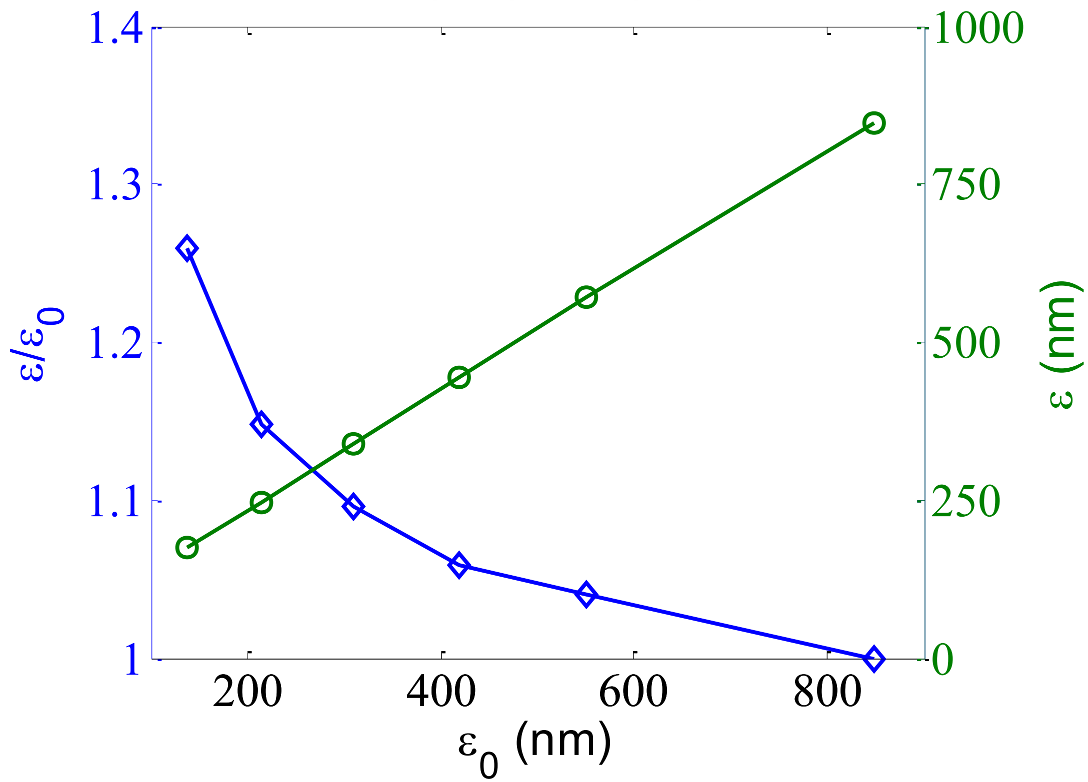


- We measured less emittance blow-up starting from a larger slice emittance uncompressed bunch
- We simulated bunches at the entrance of the bunch compressor with different initial core emittances

**MEASUREMENTS**




**SIMULATIONS**




The larger the initial slice emittance, the smaller the relative core emittance blow-up is

# Discussion



- **The simulations using the 1D model of CSRTrack or Elegant do not show any core emittance increase with the bunch compression**

- **Using the 3D model of CSRTrack a core emittance increase is observed:**
  - The dependency of the core emittance increase on the different beam setup qualitatively reproduces the behavior observed at SITF, and in particular:

| Variable | Emittance growth |
|---|---|
| Compression factor | Linear |
| Beam energy | Independent |
| Chicane bending angle | Smaller for smaller bending angle |
| Optics ($\beta_x$ at the end of BC) | Smaller for smaller $\beta_x$ at the last dipoles |

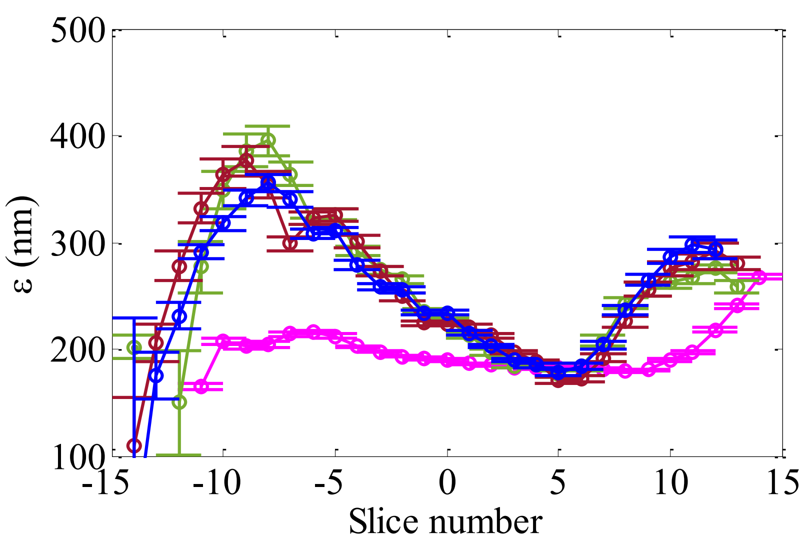
- **Measurements and simulations indicate CSR and 3D effects as the responsible for the observed core emittance increase**

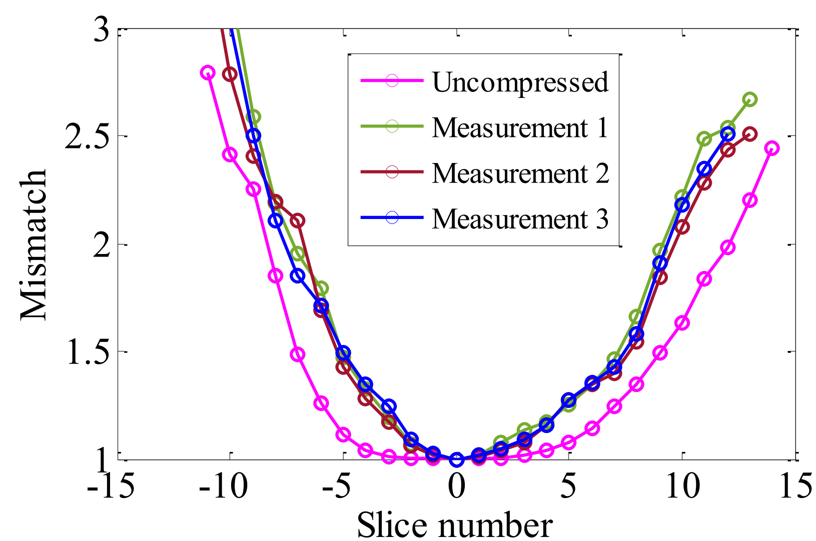
# Minimum measured core emittance



- By doing a full optimization we have achieved the following emittances for the 200 pC bunch charge:

| | Uncompressed | Compressed (CF = 8) |
|---|---|---|
| Slice emittance (nm) | 199±15* | 199±27* |




- These values **fulfill** the SwissFEL requirements



* Only statistical error included

# Conclusions



- **Measured core emittance growth during compression at SITF, and it is:**
  - Proportional versus the bunch compression factor (constant $R_{56}$)
  - Smaller for smaller chicane bending angle
  - Independent on the beam energy
  - Strongly dependent on the optics along the bunch compressor
  - Strongly dependent on the optics upstream the bunch compressor
- **Using 3D model including CSR reproduced qualitatively all the measured dependencies**
- **Excluded some possible sources for the core emittance blow-up:**
  - Resolution limit of the measurement
  - Slice energy spread via chromaticity or spurious dispersion
  - Horizontal tilt along the bunch
- **CSR and 3D effects considered to be the main responsible for the observed phenomenon**
- **Measured ~200 nm slice emittance along a small fraction (flatness of the mismatch) and less than 300 nm for the majority of the bunch length**

# Acknowledgment




**We would like to thank**

**all the groups involved in the SwissFEL Test Facility**

**and you for the attention**