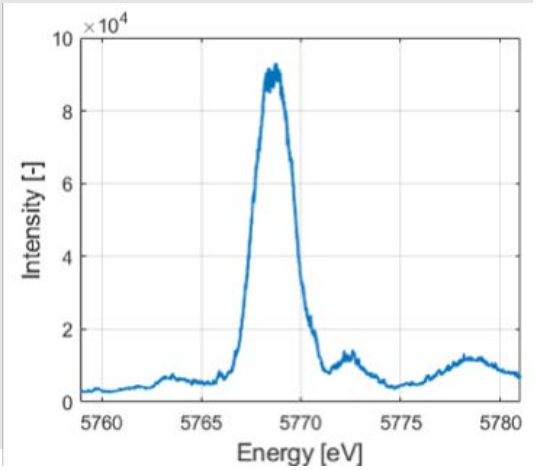
PAUL SCHERRER INSTITUT

PSI



Generation of Sub-femtosecond X-ray Pulses at SwissFEL

Alexander Malyzhenkov :: SwissFEL Beam Dynamics :: Paul Scherrer Institut

Co-authors: Y. Arbelo, P. Dijkstal, S. Bettoni, P. Craievich, E. Ferrari, S. Reiche, P. Juranic, E. Prat

Free-Electron Laser Conference 2019, Hamburg

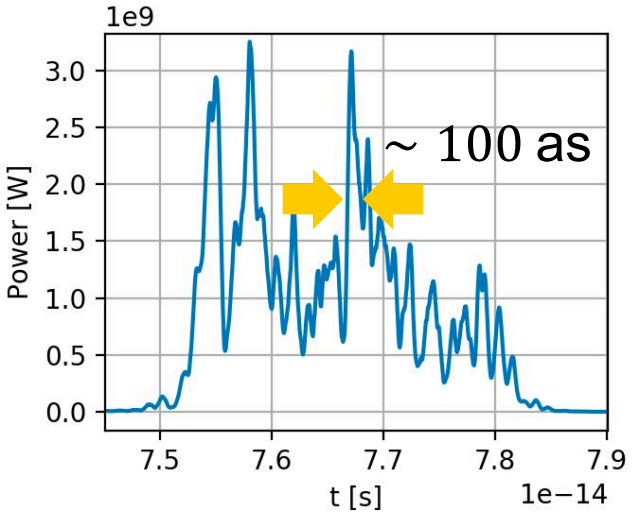
27 August

Longitudinal coherence of SASE* FELs

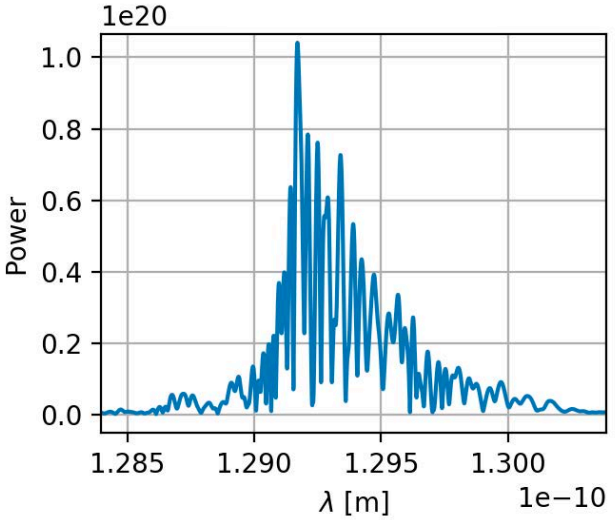
*SASE=Self Amplified Spontaneous Emission

Partial longitudinal coherence (long electron bunches):

Time domain



Frequency domain

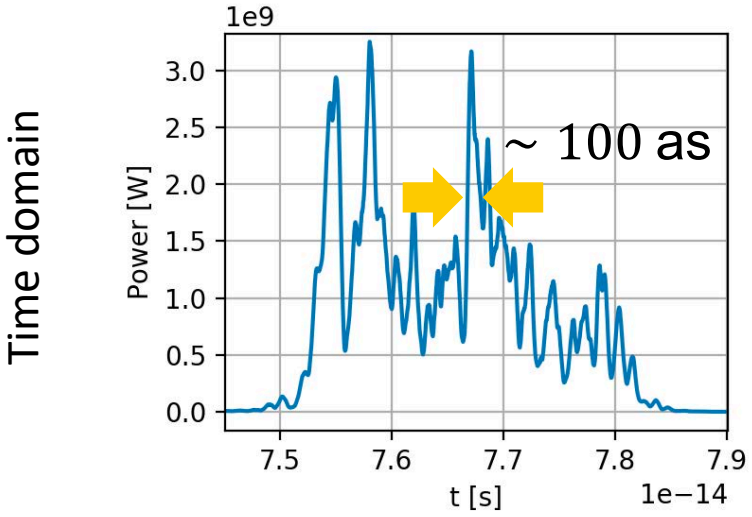


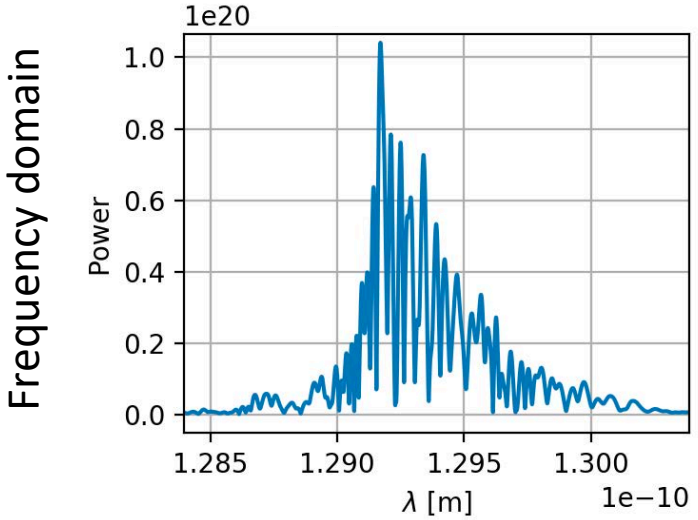
Mode (or spike) duration = slippage within the gain length

e.g. coherence length = cooperation length

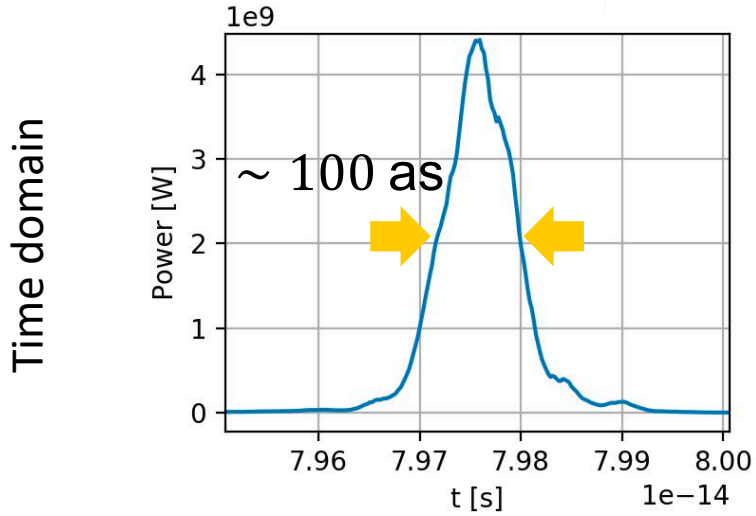
Longitudinal coherence of SASE FELs

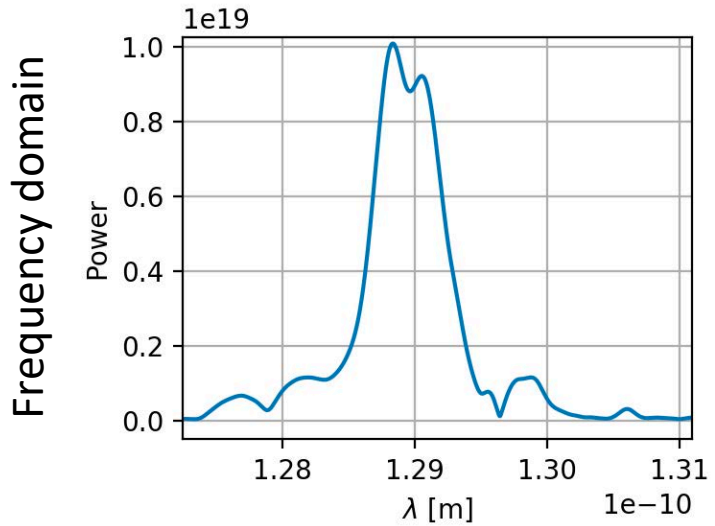
Partial longitudinal coherence (long electron bunches):





Full longitudinal coherence (short electron bunches ~ few coherence lengths):



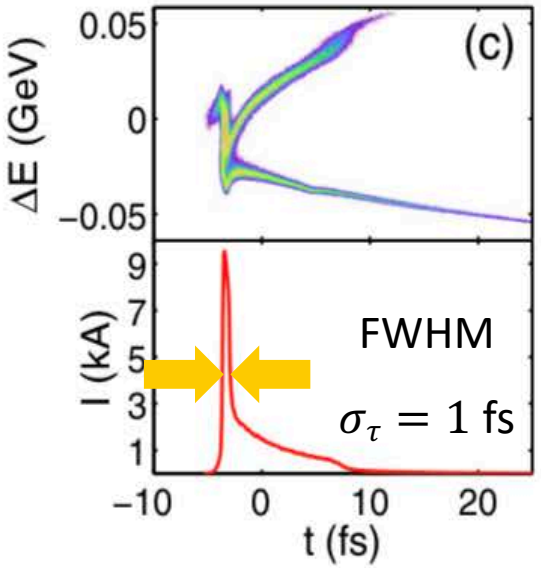


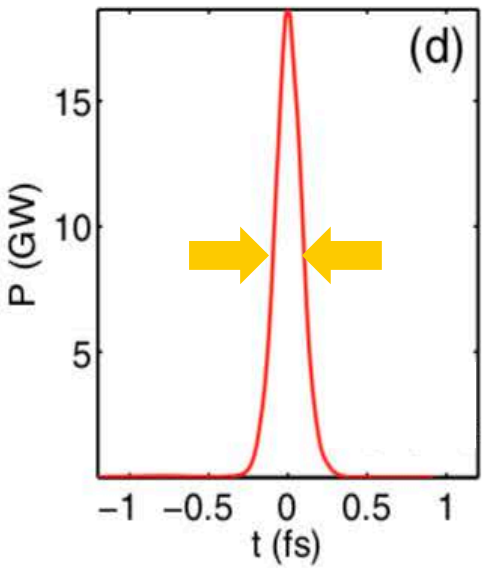
Single spike SASE FELs

1. Ackermann *et al*. "Operation of a free-electron laser from the **extreme ultraviolet** to the water window," Nat. Photonics 1, 336 (2007) **@DESY [Nonlinear compression w/o X-band]**
2. Huang *et al*. "Generating **Single-Spike** Hard X-Ray Pulses **with Nonlinear Bunch Compression** in Free-Electron Lasers," PRL **119**, 154801 (2017) **@LCLS:**

Hard X-ray
$\lambda = 0.2$ nm

Single spike = Sub-fs pulse





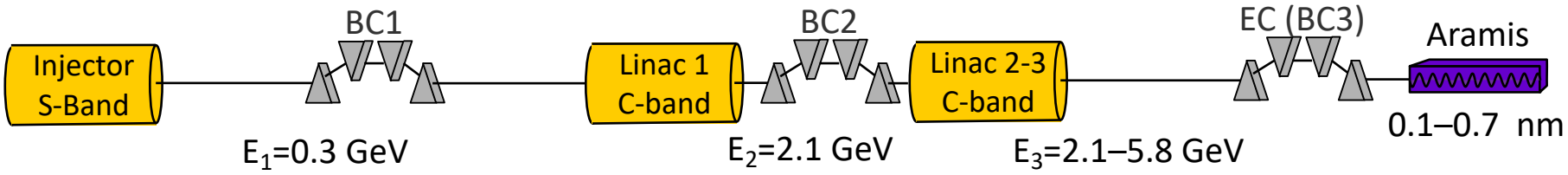
FWHM

$\sigma_\tau = 190$ as

Nonlinear compression to overcome RF jitters

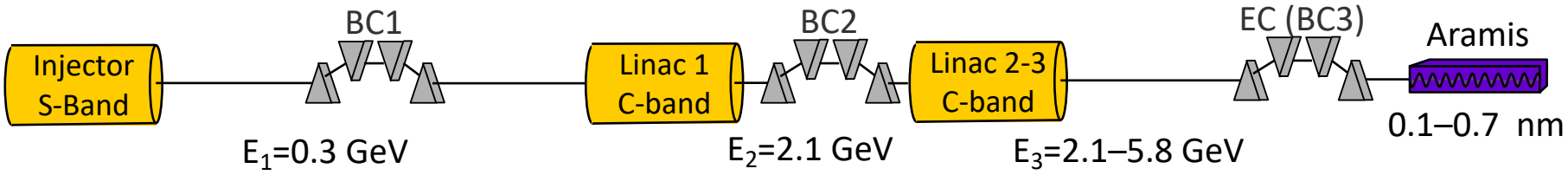
*There are other methods for generation of the Sub-fs pulses which we do not discuss here

Multi-stage compression at SwissFEL



- Adjustable dispersion R_{56} in BC1 and BC2, and Energy collimator (EC) {with quadrupoles x6}
- Two- or three-stage compressions are possible in this layout

Multi-stage compression at SwissFEL



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where: $m_i = E_i/E_{i+1}$, $c_i = (1 + R_{56_i} h_i)^{-1}$, h_i – total chirp before BC_i

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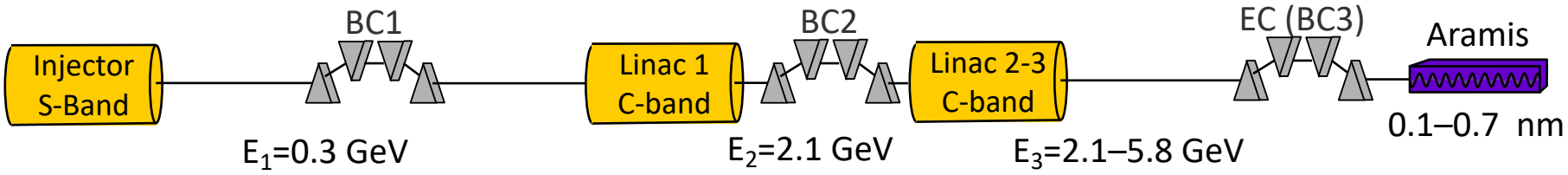

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Nonlinear compression: $c_3{}^{-1} = 0$

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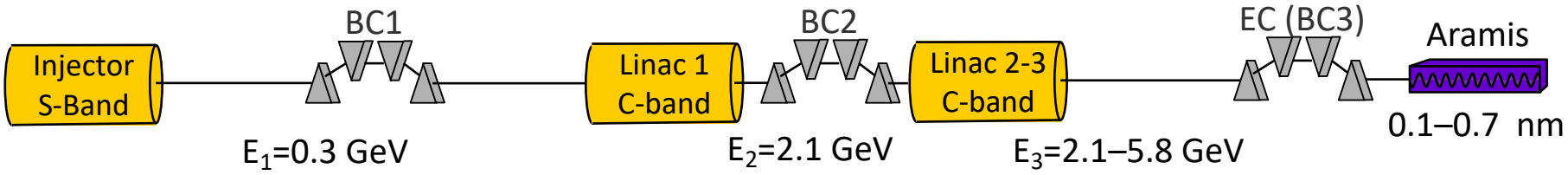

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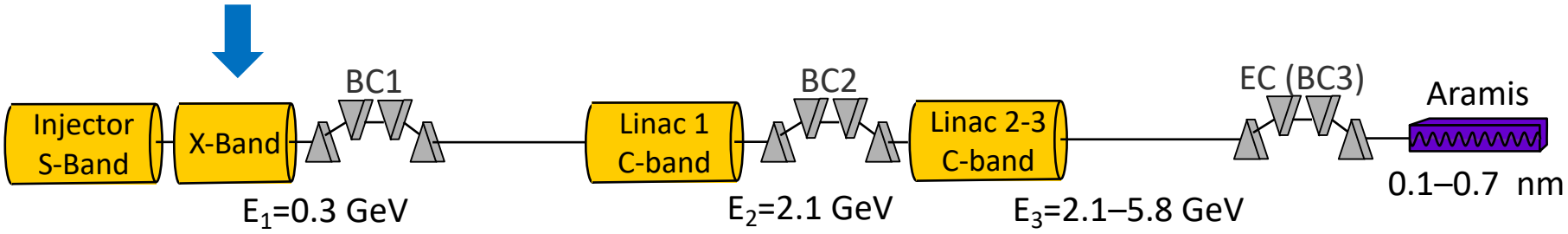

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- **"Nonlinearity"** of the full compression can be precisely controlled by **X-band**

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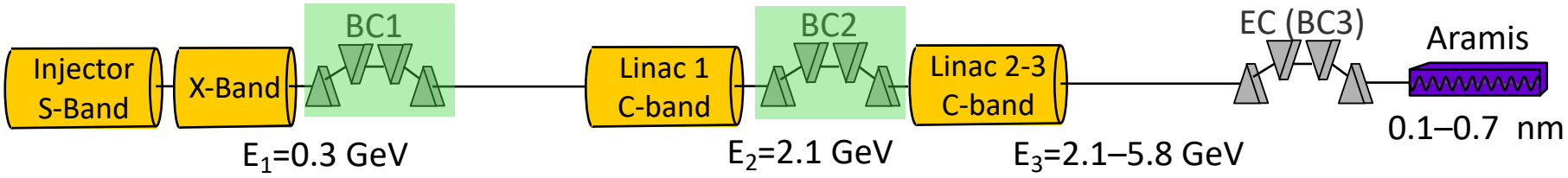

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Compress less in BC1 and BC2 for shorter pulse duration !

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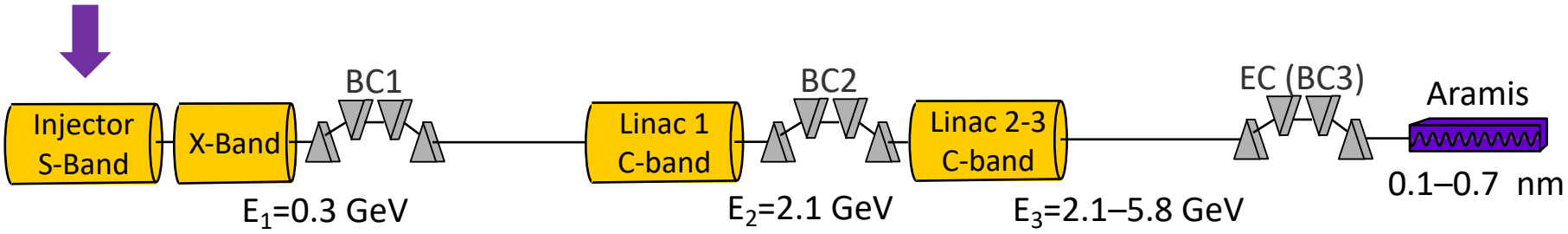
Multi-stage compression at SwissFEL



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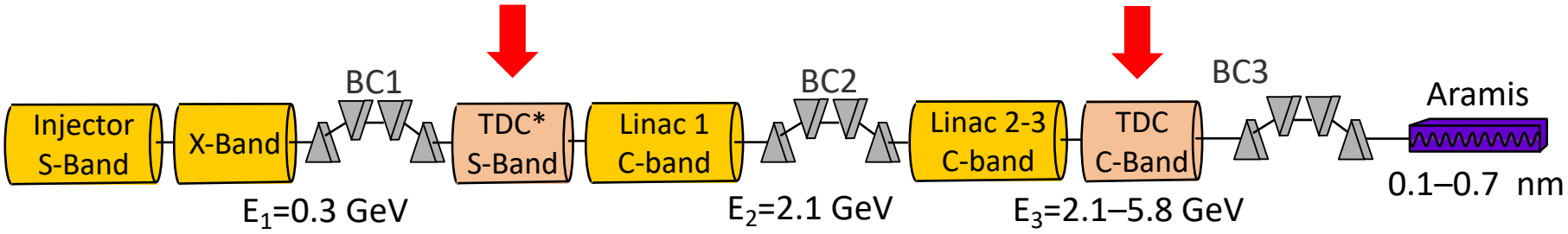
- **Tunability:** compression factors + laser heater

Compress less in BC1 and BC2 for shorter pulse duration !

Nonlinear compression: $c_3^{-1} = 0$

Full compression: $c_3^{-1} = 0, B_3 = 0$

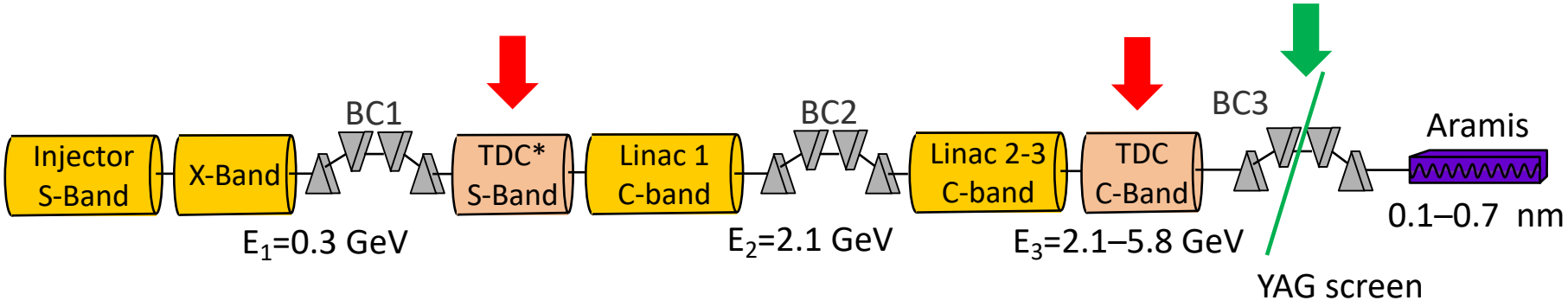
Longitudinal diagnostics at SwissFEL



*TDC=Transverse Deflecting Cavity

- S-Band and C-Band TDCs (R_{45}) are used for the time diagnostics: $-ct \rightarrow y' \rightarrow y$

Longitudinal diagnostics at SwissFEL



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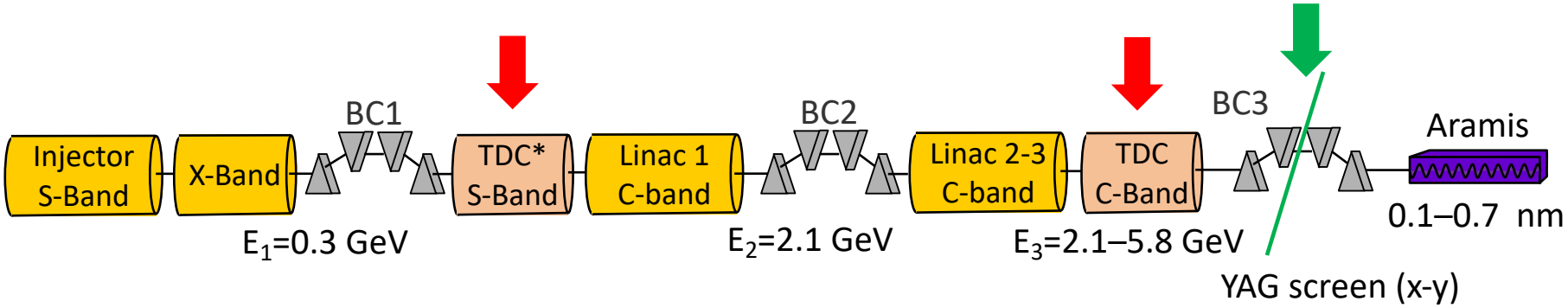
Longitudinal diagnostics at SwissFEL



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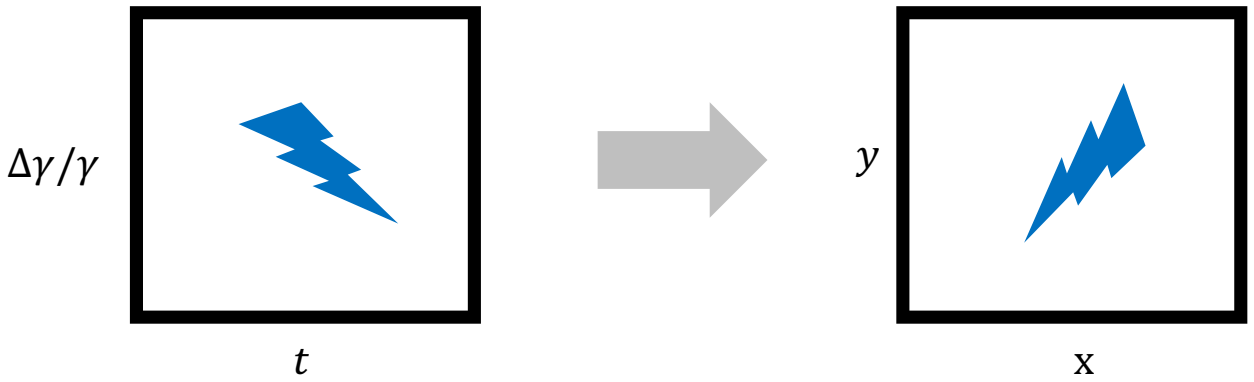
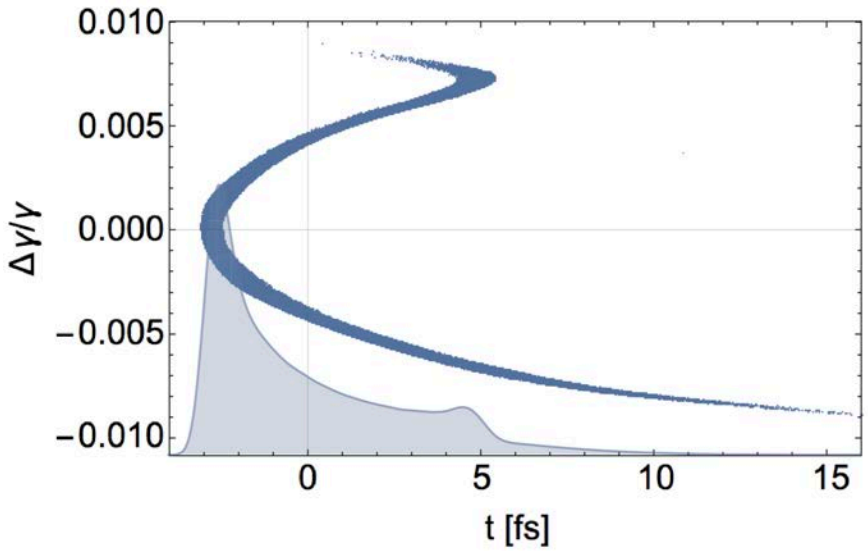


Nonlinear compression: simulations

Electron beam phase space (ASTRA+ELEGANT):

2-stage:



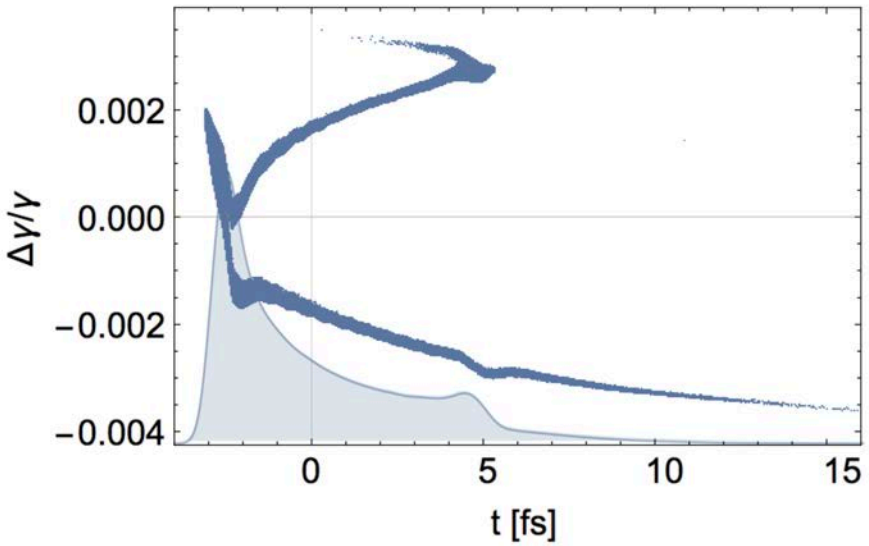
Right after BC_2

C-shape due to nonlinear compression

Nonlinear compression: simulations

Electron beam phase space (ASTRA+ELEGANT):

2-stage:



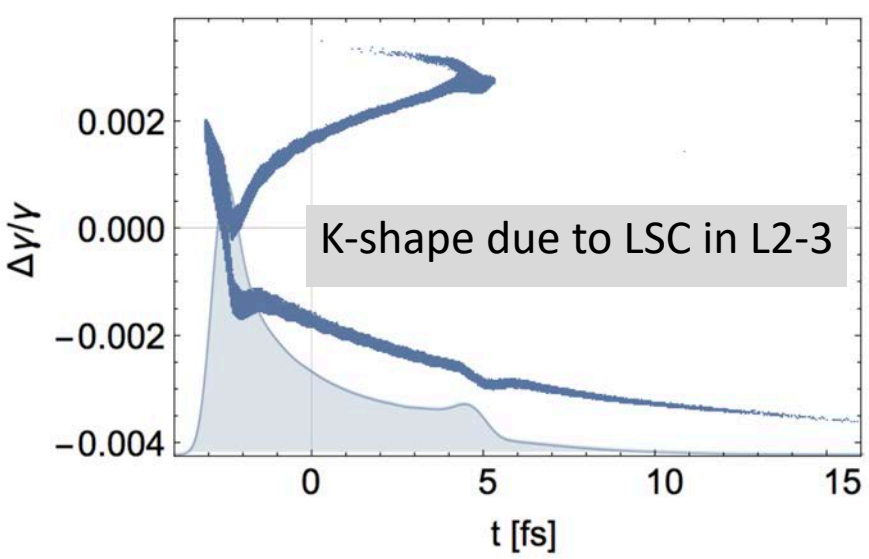
At the undulator entrance

K-shape due to Longitudinal Space Charge (LSC) effects in Linac 2 and 3

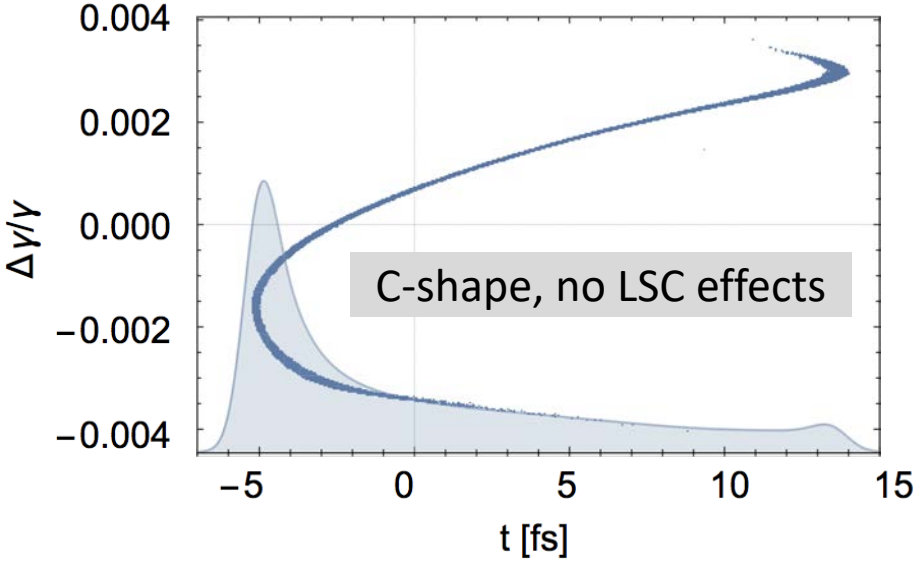
Nonlinear compression: simulations

Electron beam phase space at the undulator entrance (ASTRA+ELEGANT):

2-stage:



3-stage:



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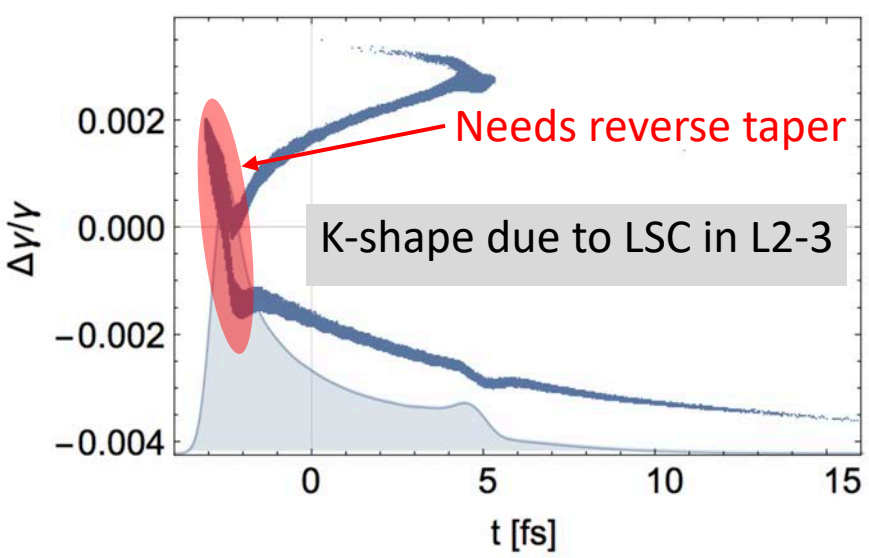

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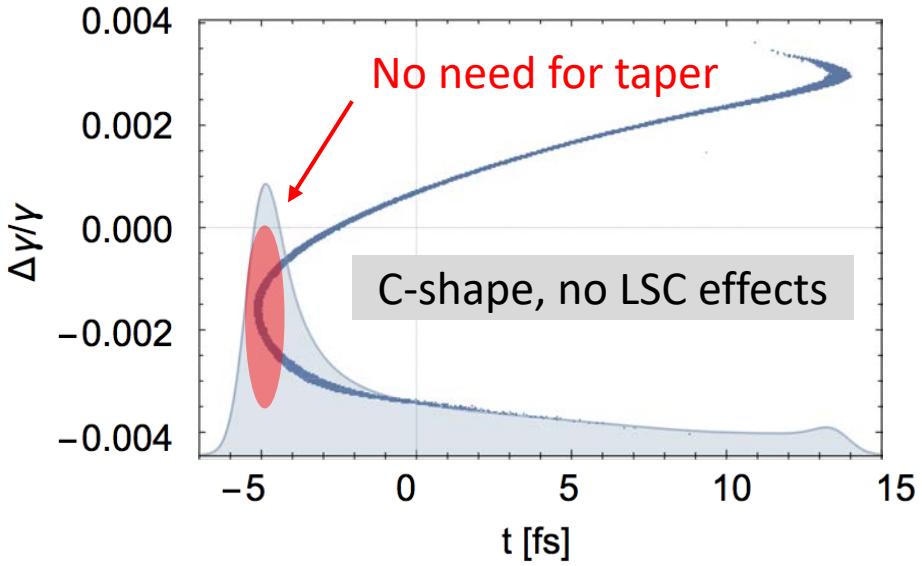
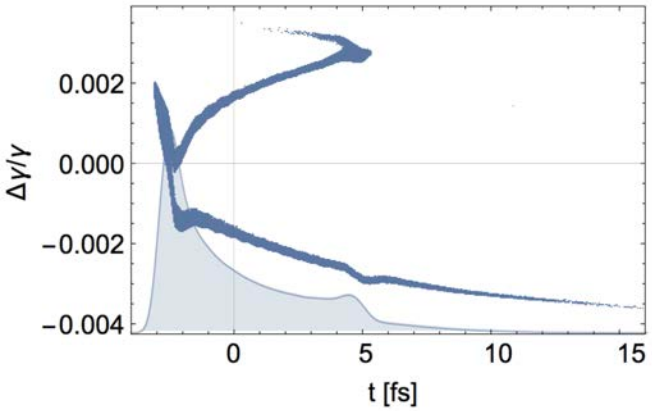


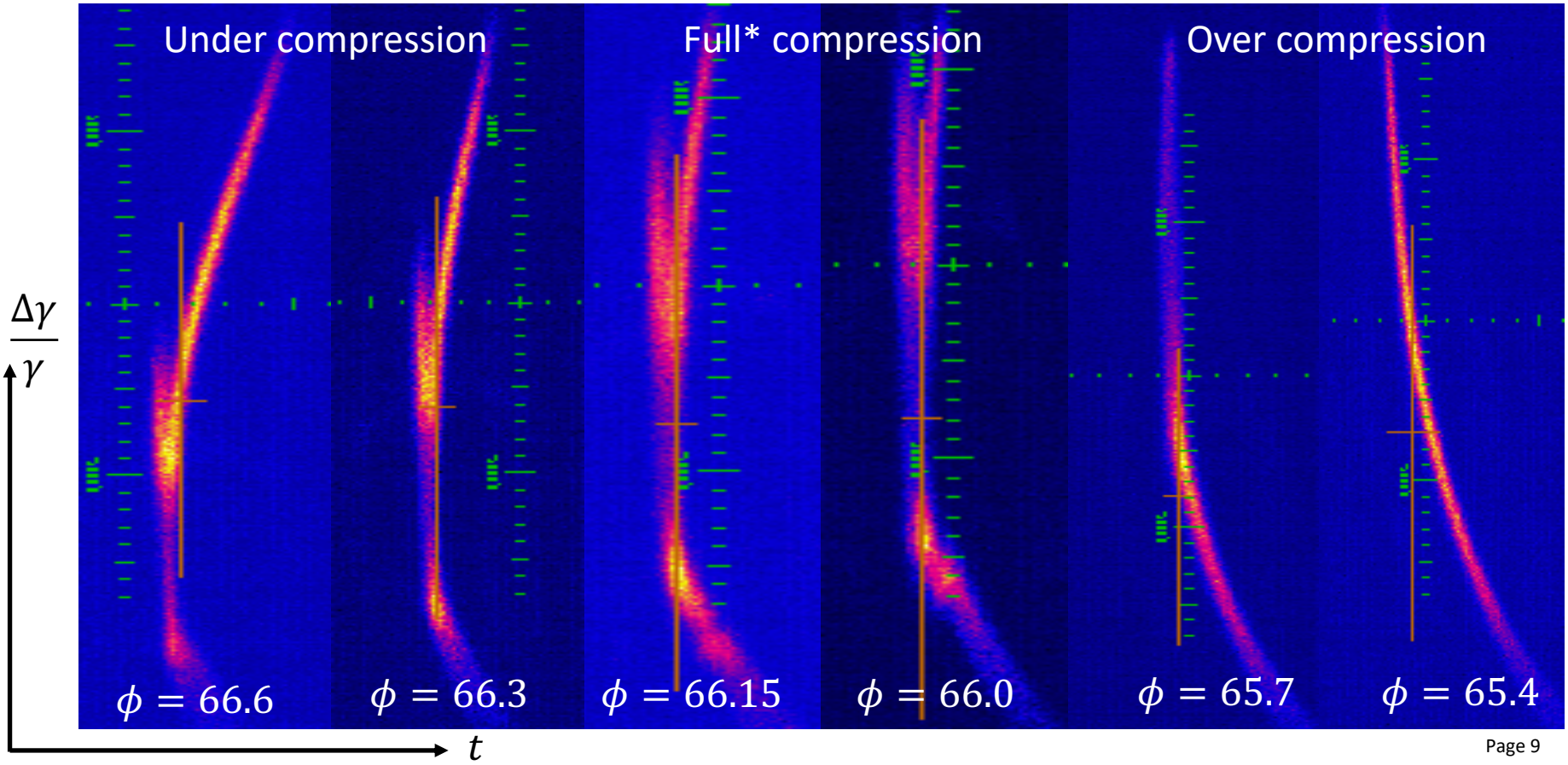
- **Advantage of the 2-stage @SwissFEL**: longitudinal phase space of the compressed beam can be measured experimentally and directly used for tuning

Tuning 2-stage compression

Adjusting the **L1 phase** while looking at the measured longitudinal phase space

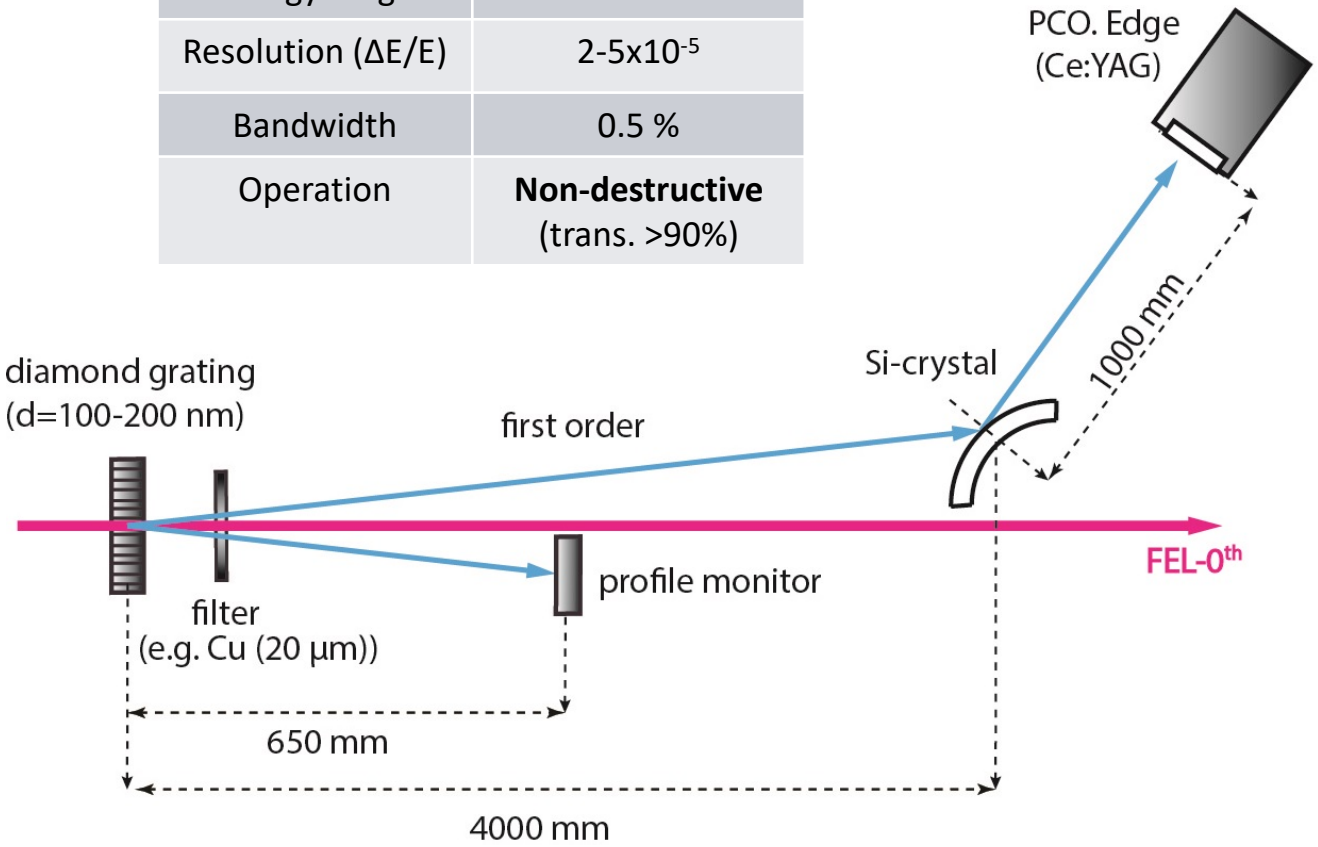


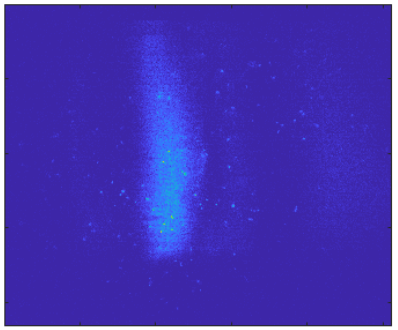
- **K-shape from simulations is benchmarked**
- **3-stage:** uncompressed beam can be measured before the EC and the energy chirp reconstructed

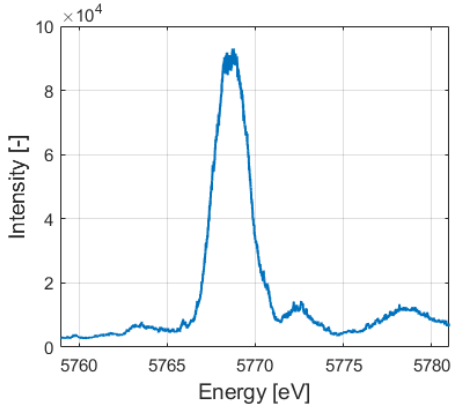


Single shot spectrometer

Integrated	Aramis beamline
Energy range	**4 to 13 keV**
Resolution (ΔE/E)	2-5x10^{-5}
Bandwidth	0.5 %
Operation	**Non-destructive** (trans. >90%)

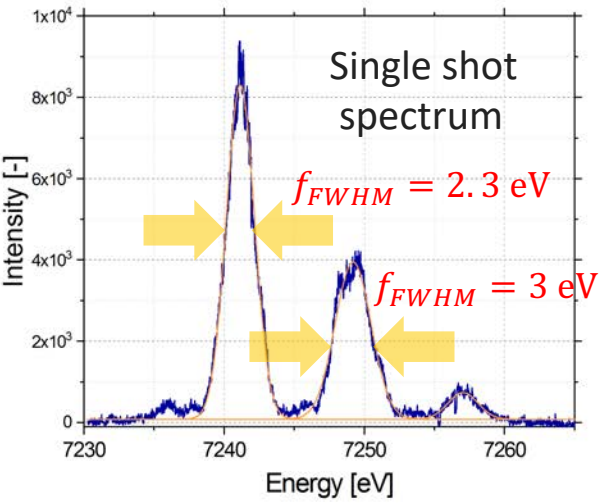


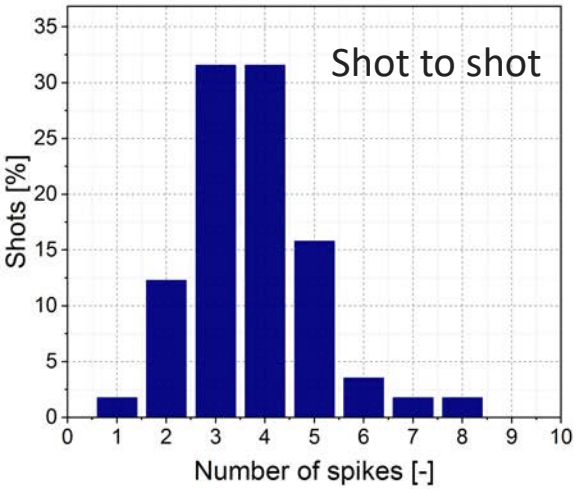




J. Rehanek, et al., *J. Instrum.* **12**, P05024 (2017)
M. Makita, et al., *Optica* **2**, 912 (2015)

Data Analysis of the acquired spectra and reconstruction of the pulse duration





Spike width and number analysis:

- Multiple Gaussian fitting in frequency domain (R^2>0.95)
- Fourier limited approximation:
  - Number of spikes in time and frequency domain are identical

[Data histogramms are courtesy of Y. Arbelo]

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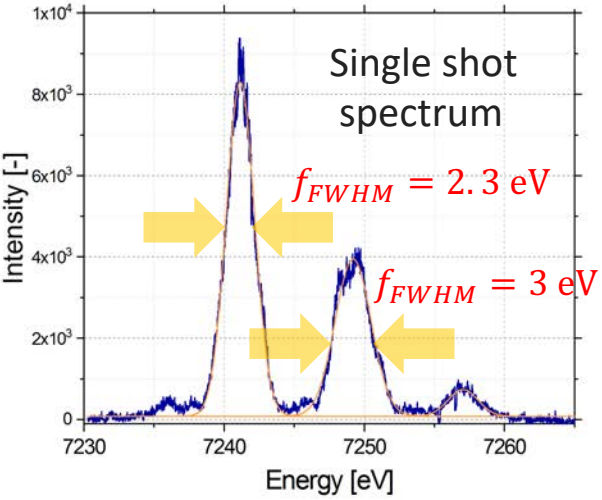

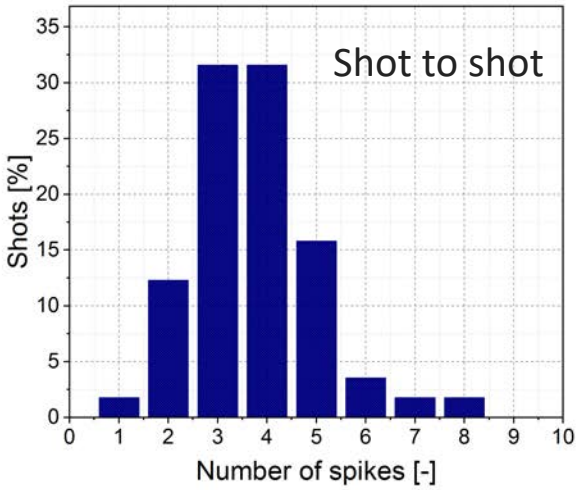

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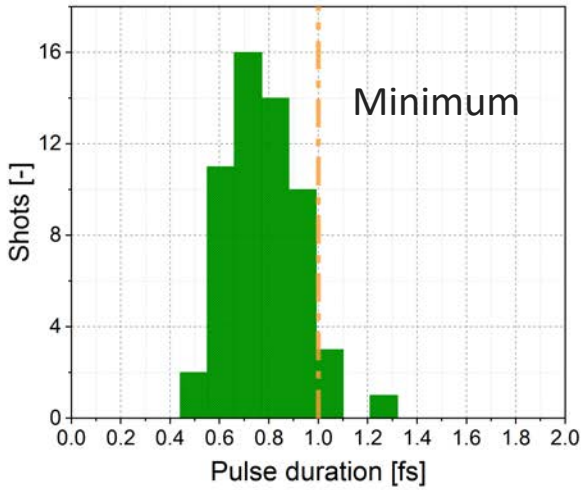
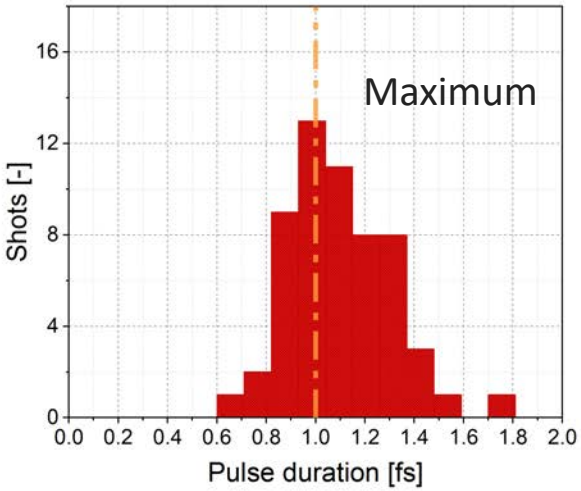




Linear chirp model:

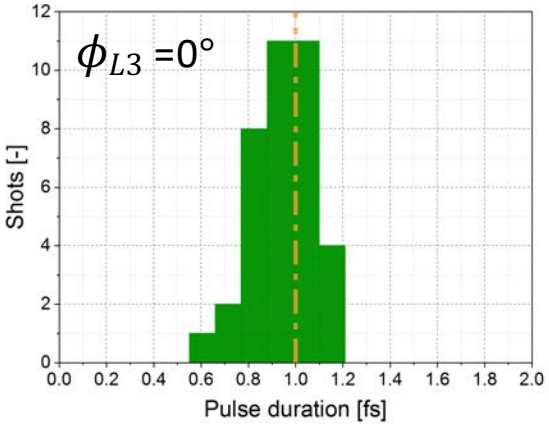
- Upper border of the pulse duration (max. chirp): ~1 fs
- Lower border of the pulse duration (no chirp): ~ 0.7 fs

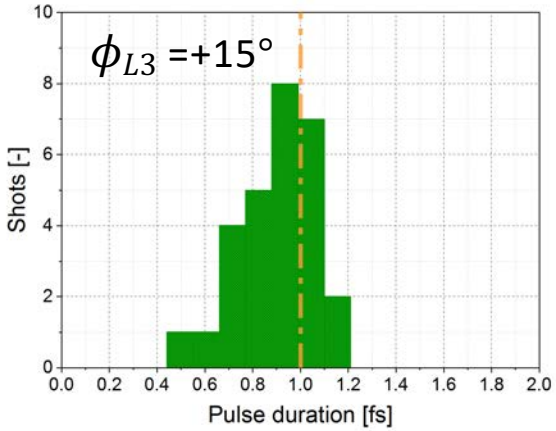
[FWHM]

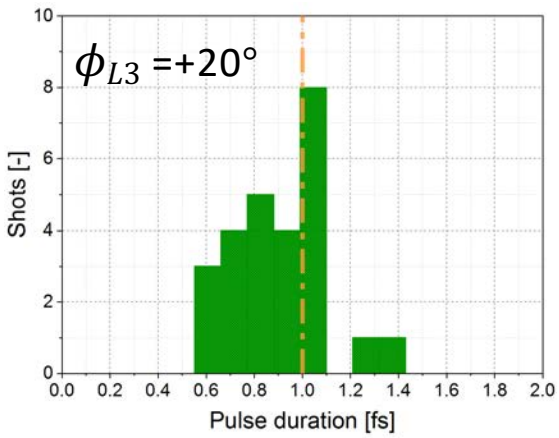
[Data histogramms are courtesy of Y. Arbelo]

Stability of the 3-stage compression

- **Main advantage of the 3-stage compression → Super-stable design**
- RF Phase in Linac 3 was varied: $\pm 15°, \pm 20°, 0°$:







- Stability from RF phase jitter in L0, L1 can be trialed the same way

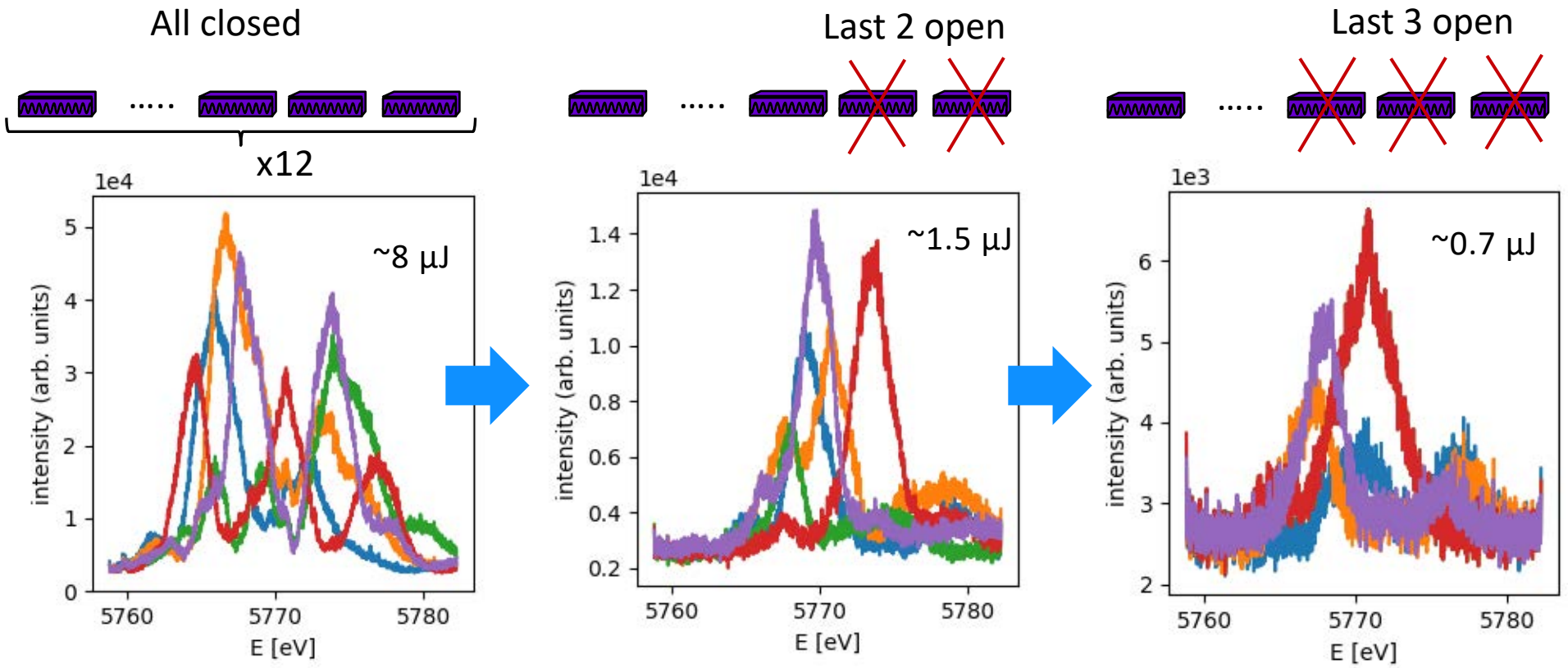
*Fat overlapped spikes are excluded from analysis

[Data histogramms are courtesy of Y. Arbelo]

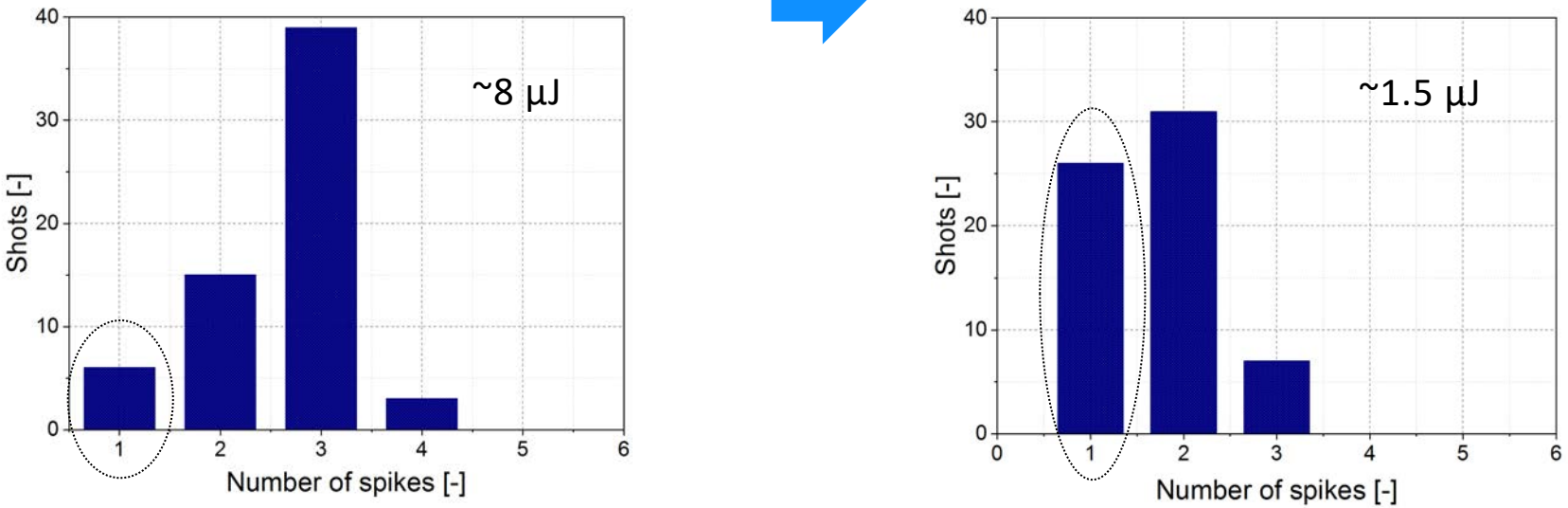
3-stage compression: undulator dependence experiment (spectra)

Simulations predicted reducing the number of spikes in the frequency domain by opening up undulators: this was confirmed experimentally.

PSSS Spectra along the undulator (5 shots each):



3-stage compression: undulator dependence experiment (histograms)



[Data histogramms are courtesy of Y. Arbelo]

Summary (main results)

- ✓ Analytical model in the linear and 2nd/3rd order approximation was used to find optimum compression scheme
- ✓ Electron bunch was strongly compressed using nonlinear multi-stage compression
- ✓ Single spike spectra validating ultra-short pulses were acquired
- ✓ Photon pulse durations of less than 1 fs FWHM were reconstructed for variable photon energies (4-12 keV)

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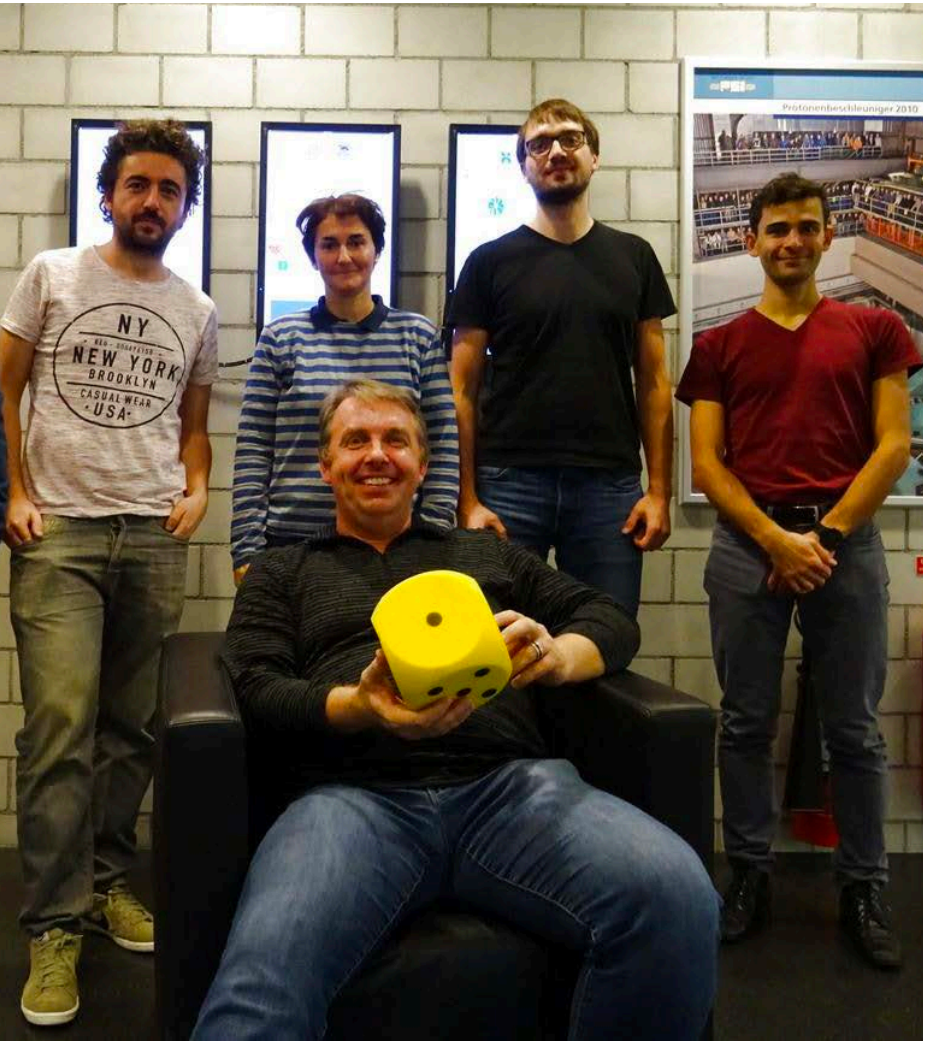
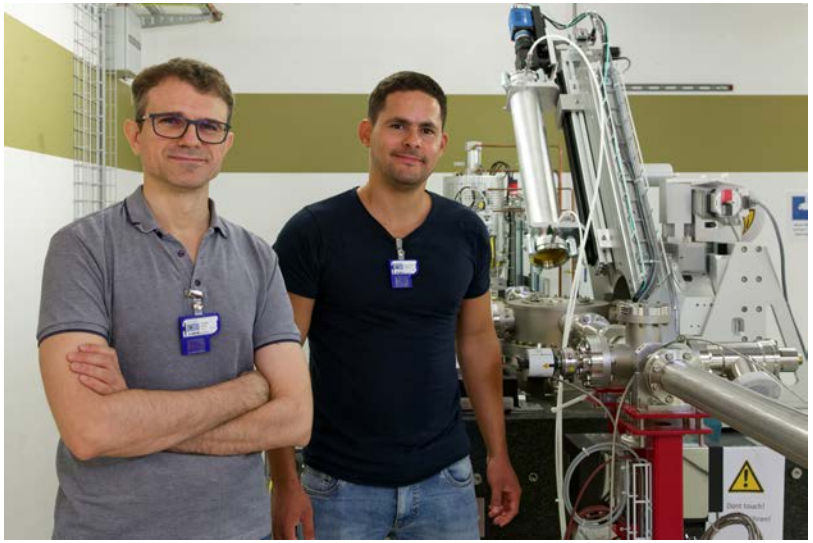
Thank you for your attention!

FEL Beam Dynamics:



Photon Diagnostics:



RF group: