Characterisation of the MAX IV arc compressors using an S-band deflector

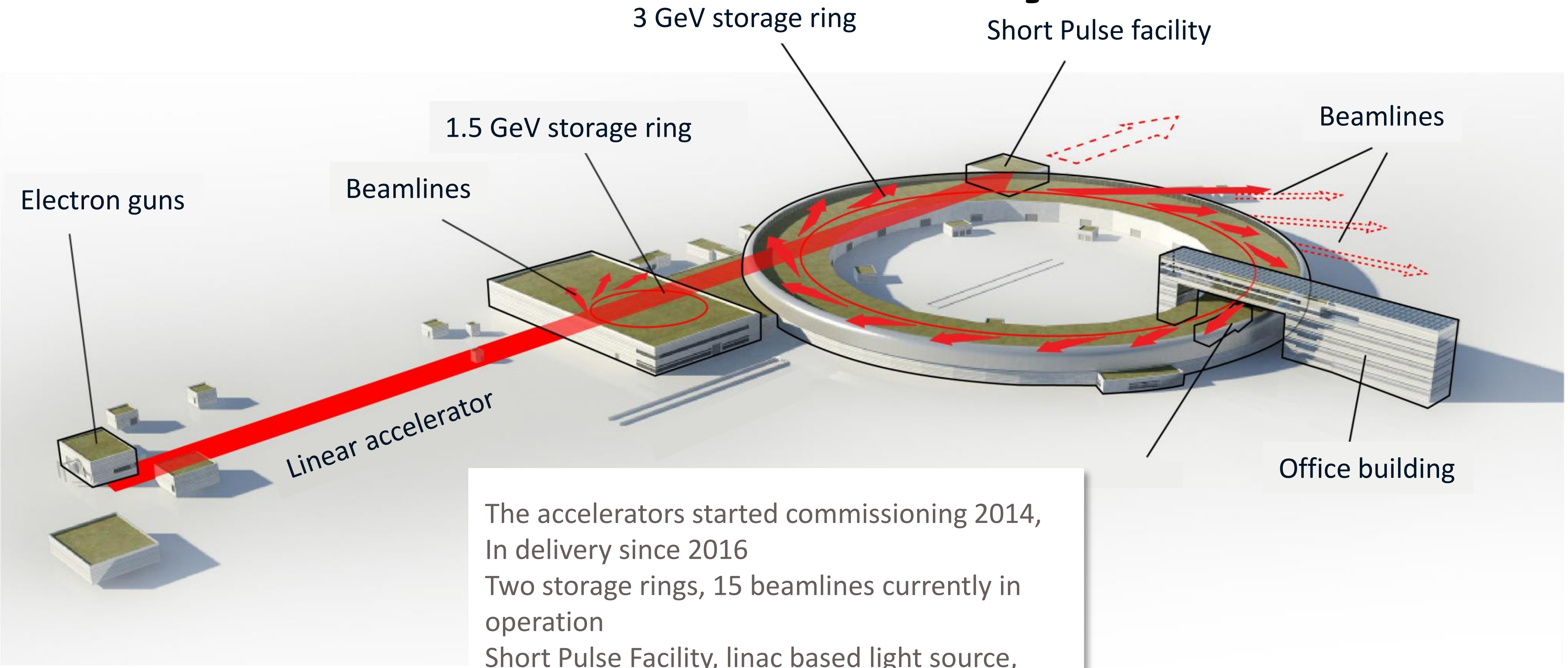
Sara Thorin

MAX IV

Overview of talk

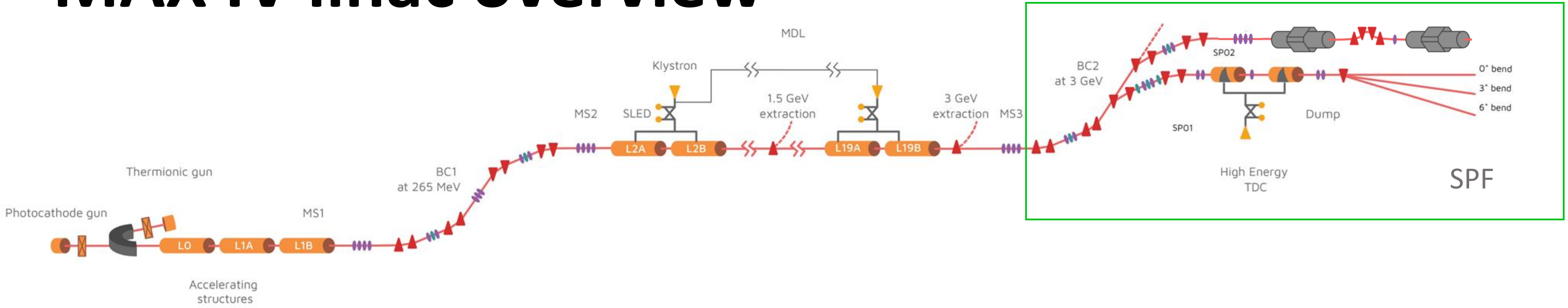
- Introduction of MAX IV
- MAX IV arc compressors - design, experience and results
- Benefits and drawbacks of arc compressors
- Experimental work – interesting measurements on the compressors using the TDC

Introduction – MAX IV facility



The accelerators started commissioning 2014,
In delivery since 2016
Two storage rings, 15 beamlines currently in operation
Short Pulse Facility, linac based light source, one user beamline - FemtoMAX

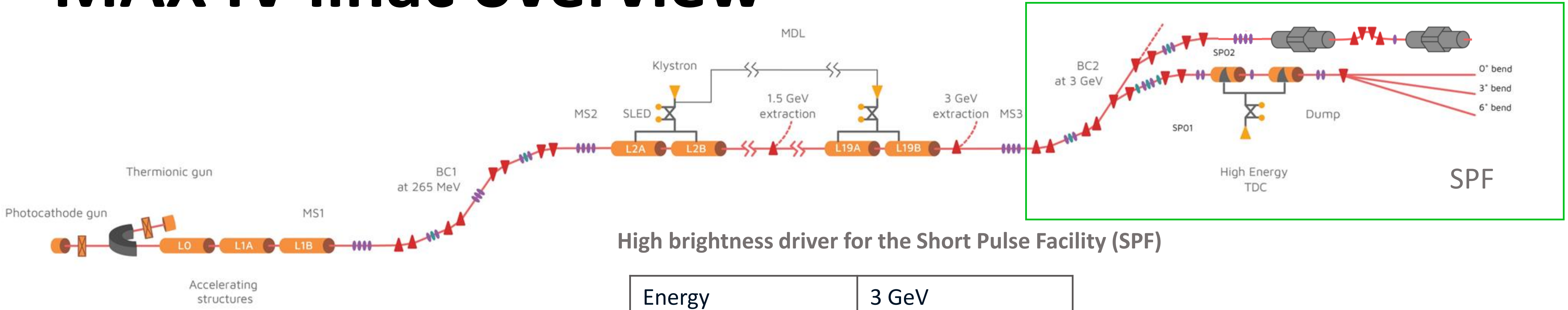
MAX IV linac overview



Full energy injection and top up operation for the two storage rings

Energy	1.5 GeV/ 3GeV
Repetition rate	10 Hz
Charge	0.3 nC/shot
Emittance	5 mm mrad
Energy spread	<0.25 %

MAX IV linac overview



High brightness driver for the Short Pulse Facility (SPF)

Energy	3 GeV
Repetition rate	10 Hz
Charge	20-200 pC
Bunch length (rms)	3 ps – 30 fs
Emittance	2-3 mm mrad
Energy spread	0.3-0.7%

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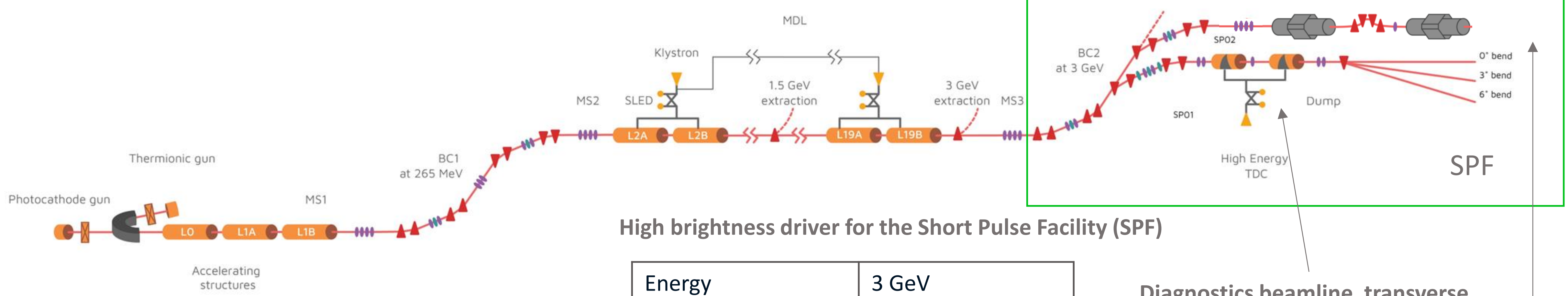

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Diagnostics beamline, transverse deflecting cavity (TDC)

FemtoMAX beamline
Ultrafast processes in solids and liquids

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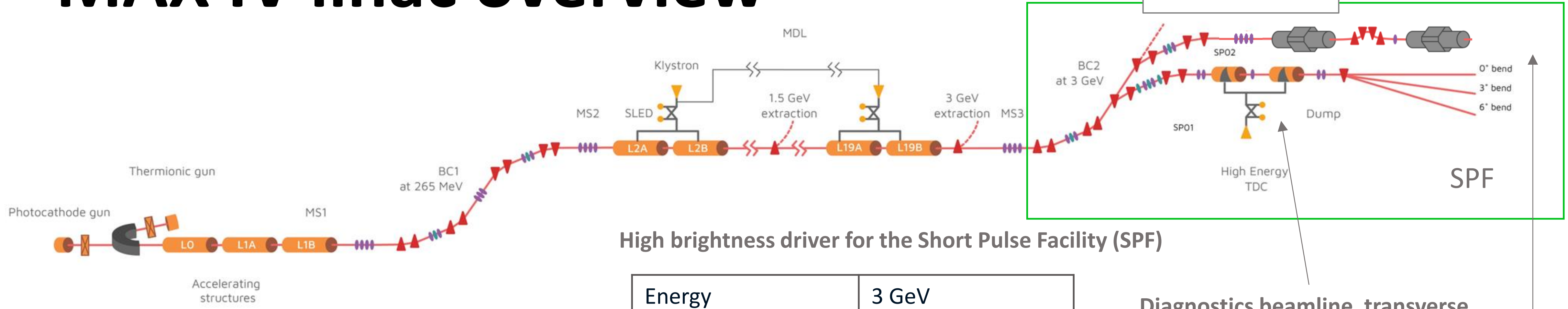
MAX IV linac overview

Possible future Free Electron Laser



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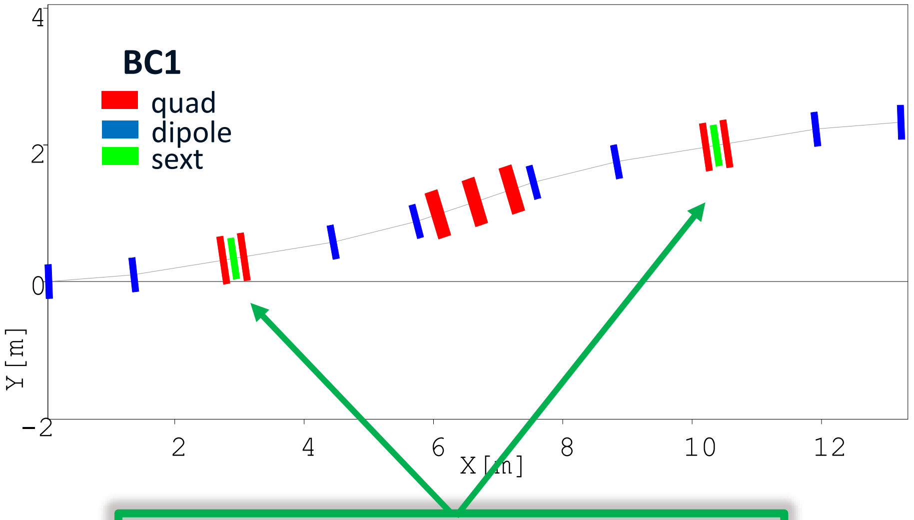
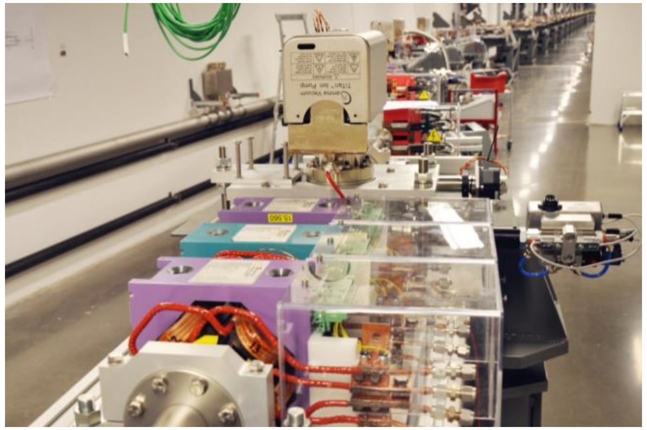
MAX IV achromat arc bunch compressors

MAX IV bunch compressors – double achromats with magnetic linearisation





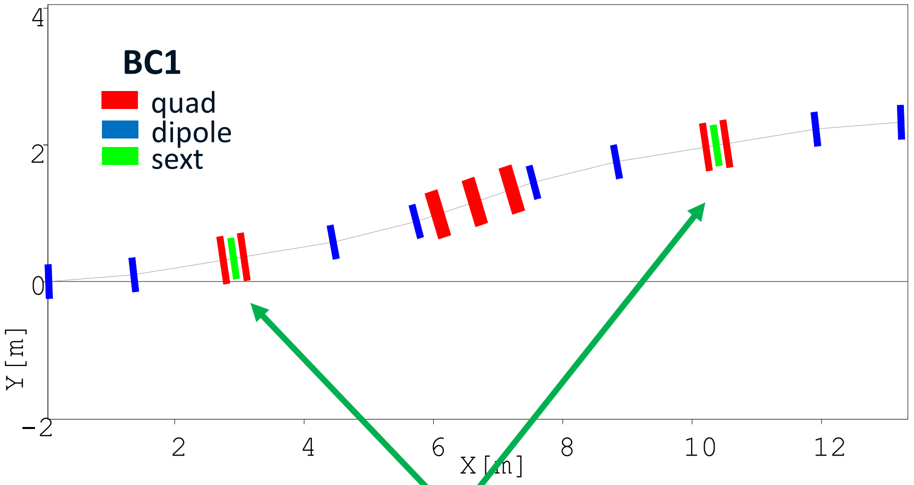
	BC1	BC2
R56	3.2 cm	2.6 cm
T566	6.6 cm	4.3 cm

Sextupoles used for both tuning T566 (=linearization) and to close second order dispersion.

$$\Delta z = R_{56}\left(\frac{\Delta E}{E}\right) + T_{566}\left(\frac{\Delta E}{E}\right)^2$$

Second order momentum compaction naturally compensates for fundamental RF curvature. The linearization effect is fine-tuned with weak sextupoles.

MAX IV bunch compressors – double achromats with magnetic linearisation



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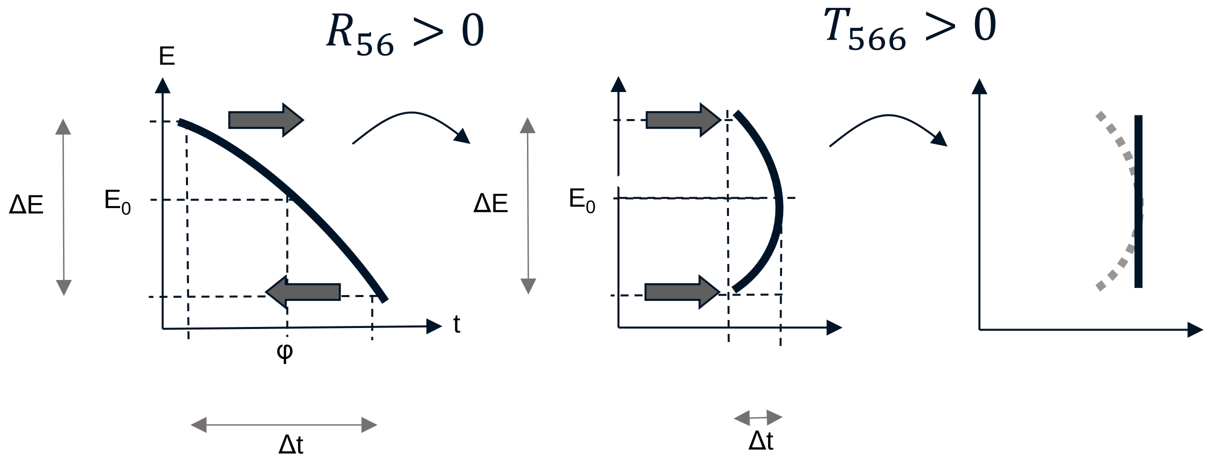
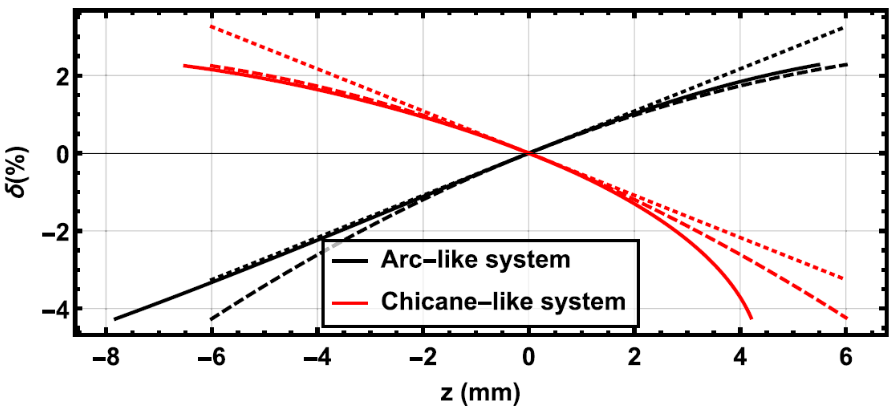


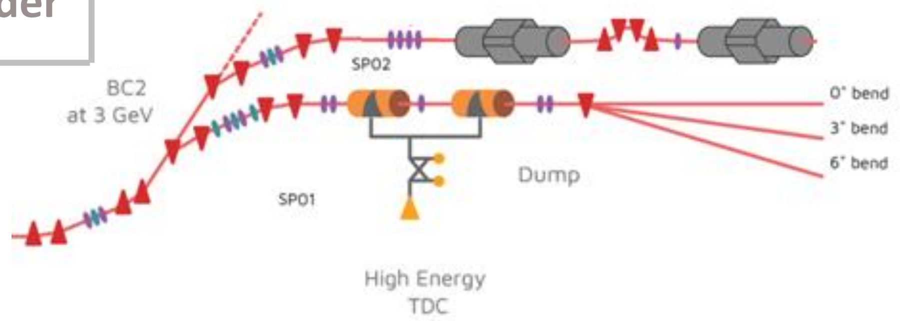


Longitudinal phase space after chirp-compression in ark-like and chicane-like systems. Comparison with linear (dotted) and curvature from fundamental RF (dashed).

Peter Williams LEDS conference Frascati 2023

MAX IV bunch compressors – double achromats with magnetic linearisation

Compressor 2 / Beam spreader



Why did we choose achromat arc compressors?

- Magnet linearisation - no need for a harmonic cavity lineariser →
  - Economy
  - Reliability
  - Simplicity
- BC2 works as beam spreader
  - FemtoMAX beamline
  - Diagnostic beamline with a TDC
- Way to give MAX IV capabilities for short pulses and a future FEL that was both cost efficient and transparent to injection.

MAX IV bunch compressors – double achromats with magnetic linearisation

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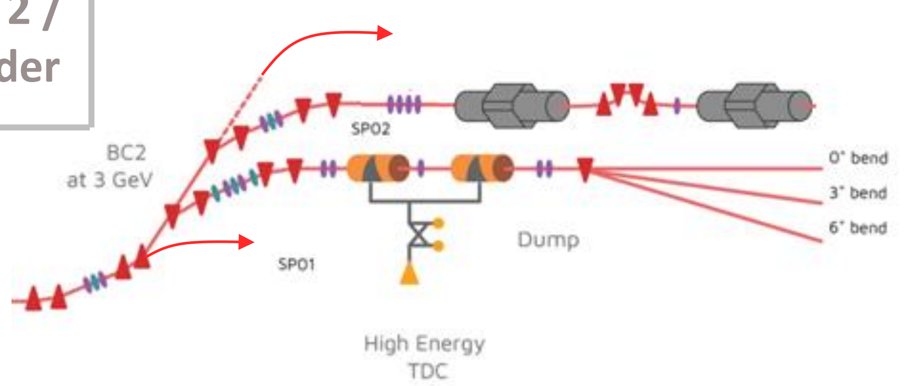

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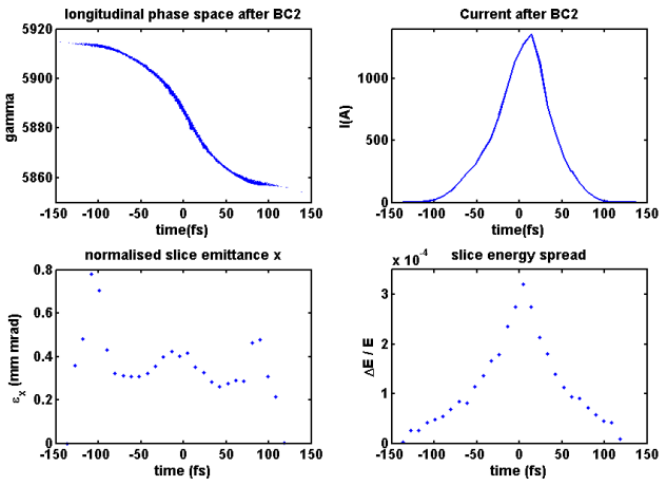
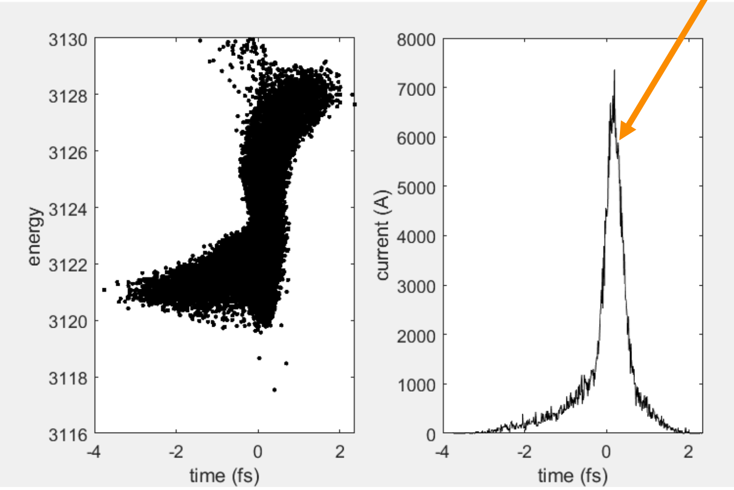
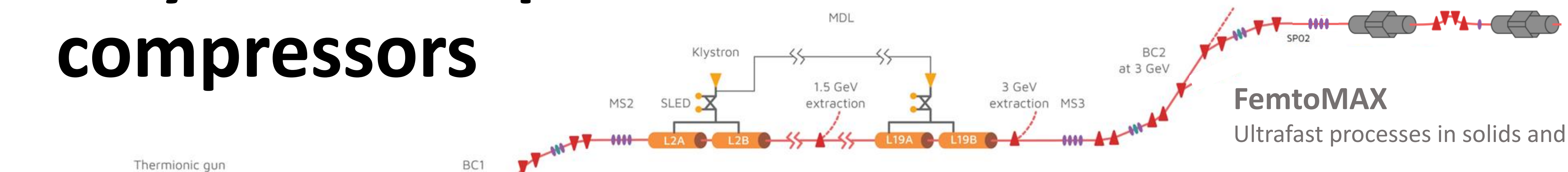
- Way to give MAX IV capabilities for short pulses and a future FEL that was both cost efficient and transparent to injection.
- Potential to make very short pulses

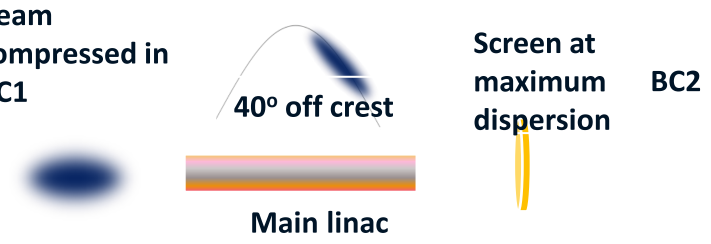


500 as fwhm



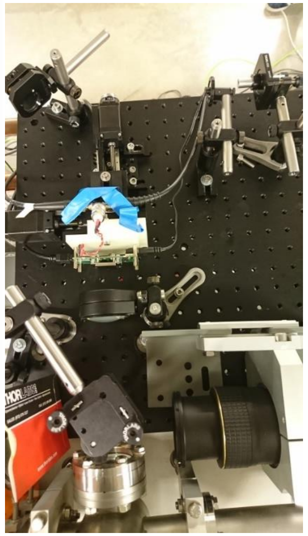
10 years of experience with the arc compressors

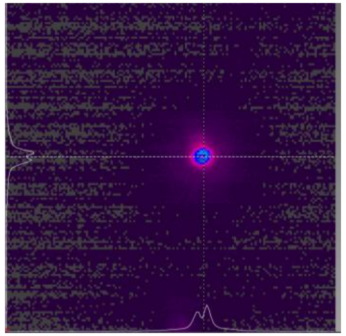




FemtoMAX
Ultrafast processes in solids and liquids

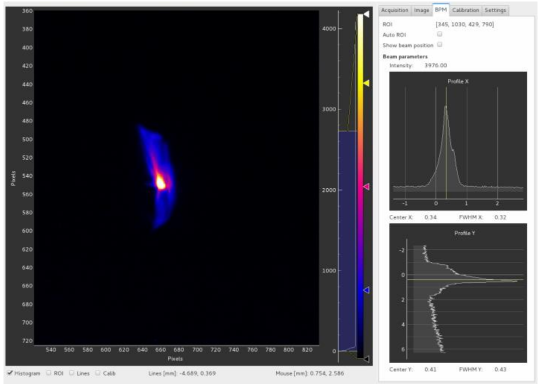
Coherent transition radiation monitor
- Intensity of the light indicates if the bunch is shorter or longer.
- Setup can give more information with further analysis
- Setup for FemtoMAX bunch length more accurate.



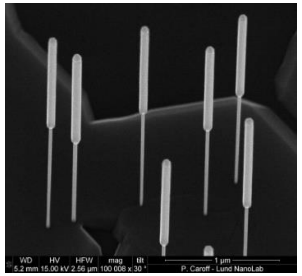


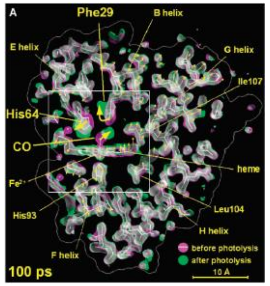
In collaboration with J. Wolfenden, T. Pacey, R. Fiorito and C. Welsch – Cockcroft Institute

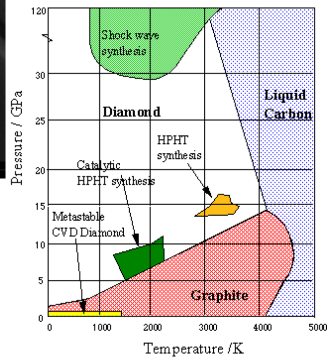
Using BC2 and linac as streak camera
- Resolution around 30 fs
- Could only measure bunch length after BC1



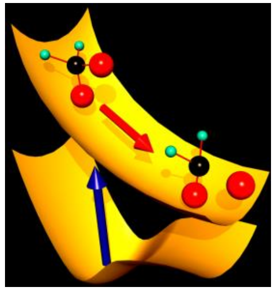
Scattering



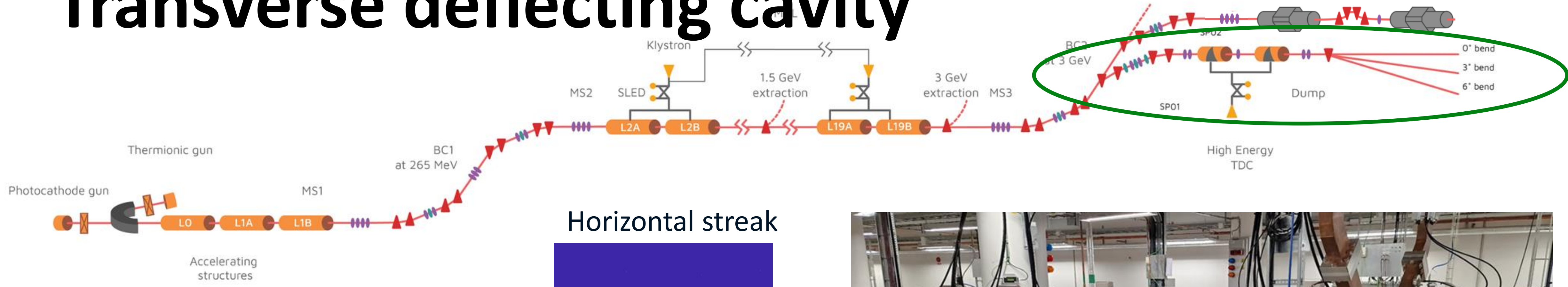




Spectroscopy

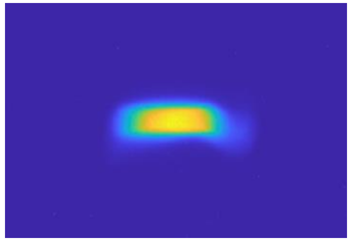


Transverse deflecting cavity

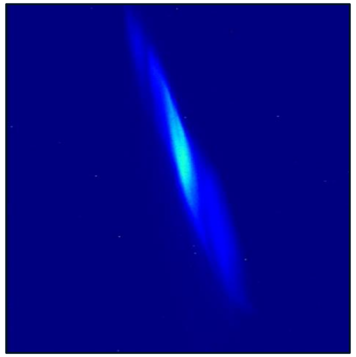


- Commissioning started during 2023
- Reached ~ 60% of full RF power
- 1 fs resolution target – reached 3 fs
- S-band (3 GHz)
- 100 MV integrated field
- Long setup
- Spectrometer dipole

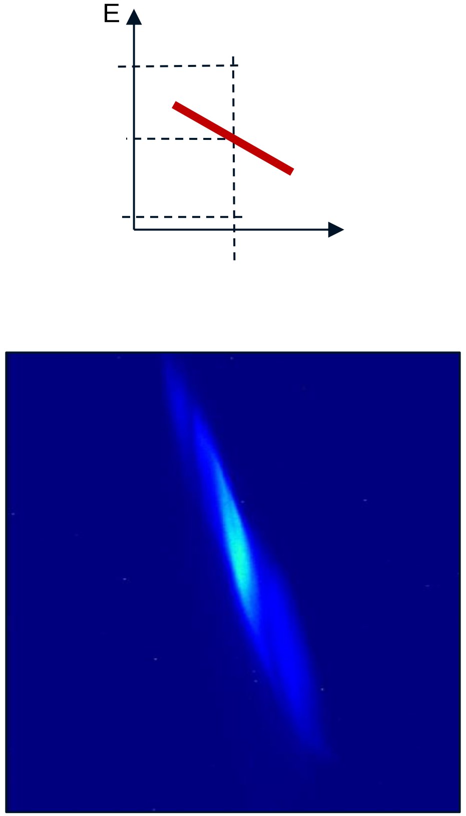
Horizontal streak

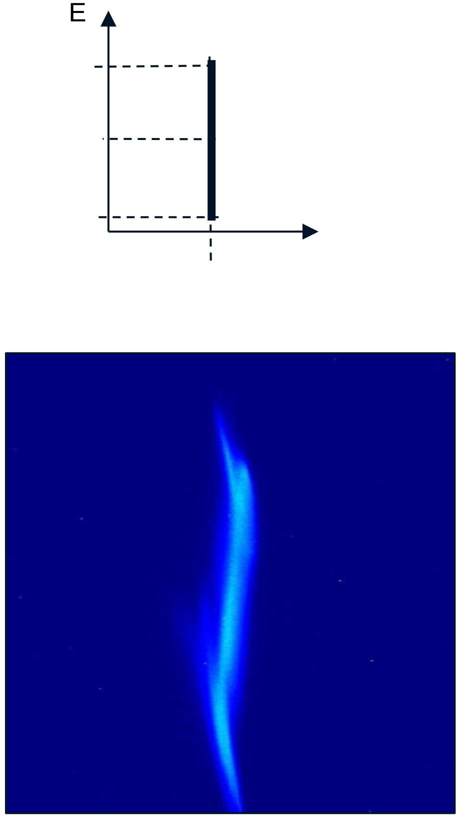


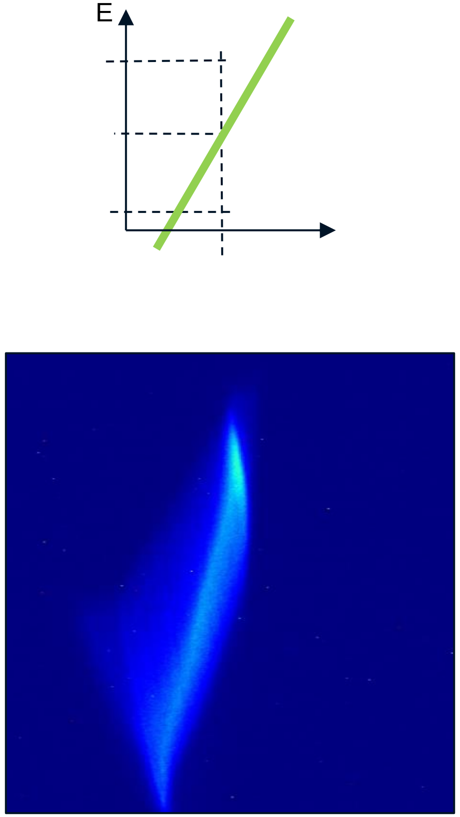
Longitudinal phase space



Compression scan – longitudinal phase space

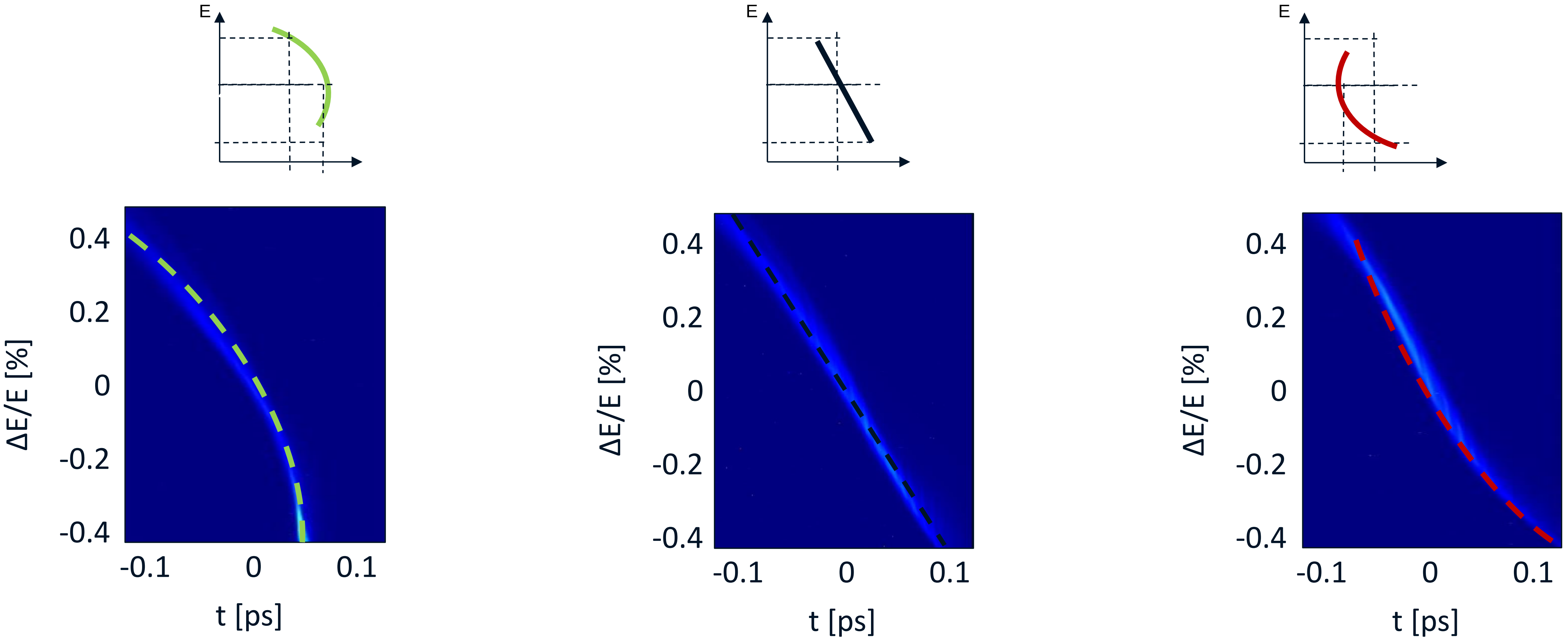






Slide from Erik Mansten, Johan Lundqvist

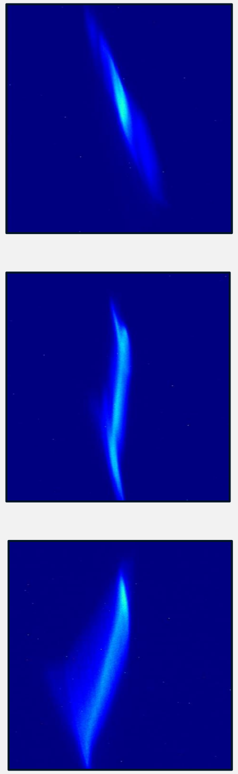
Linearization scan – Longitudinal phase space



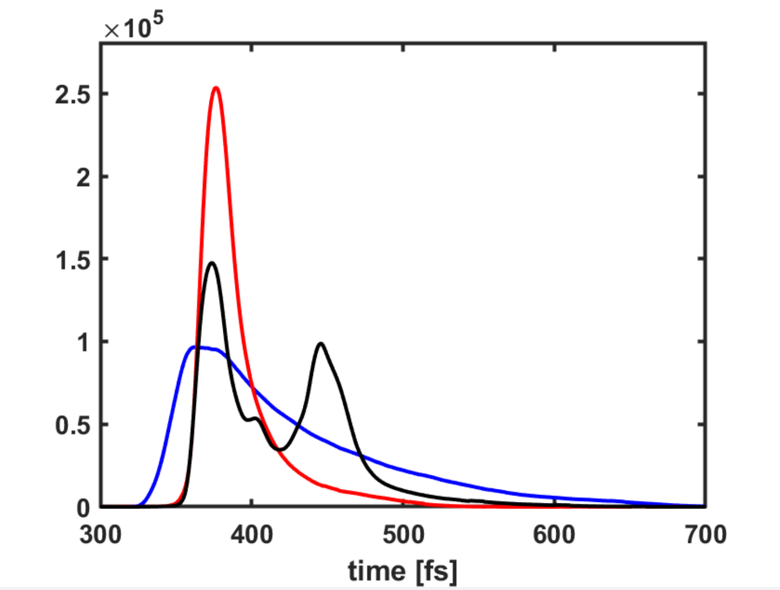
Slide from Erik Mansten, Johan Lundqvist

Compression scan – changing the phase before BC1

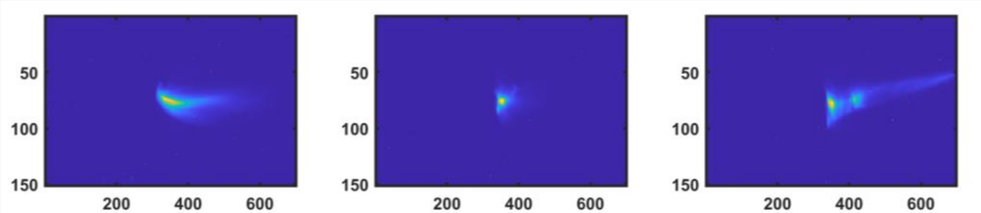
Longitudinal phase space (TDC + dipole)



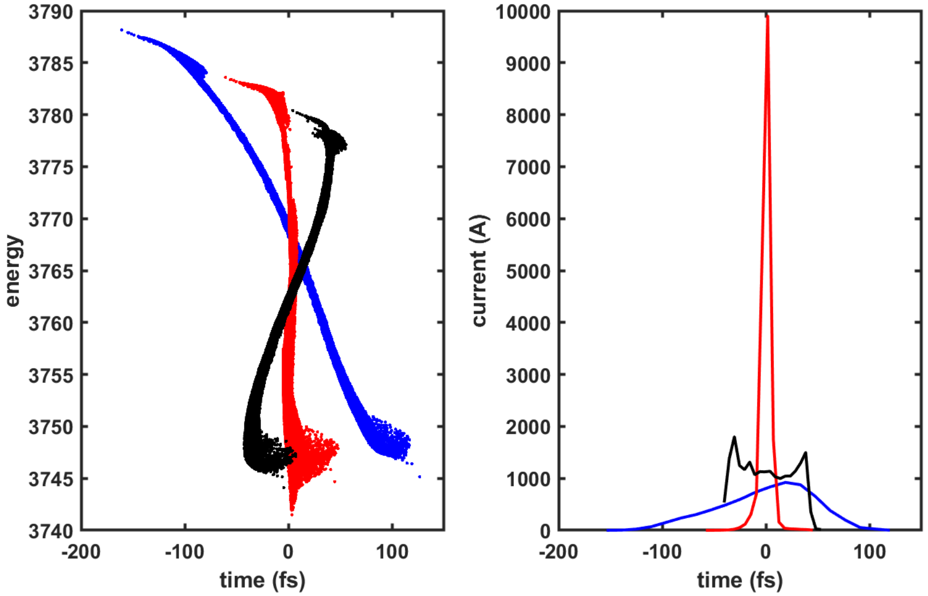
Measured electron beam at TDC after BC2



Longitudinal phase space (TDC streak)



Corresponding elegant simulation



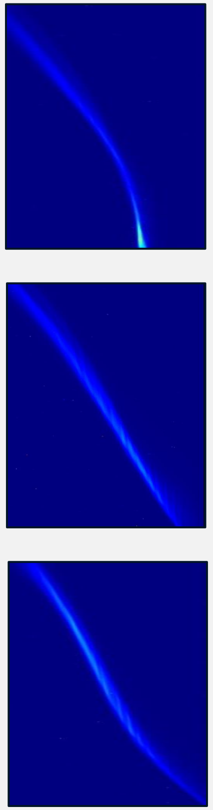
Under compressed

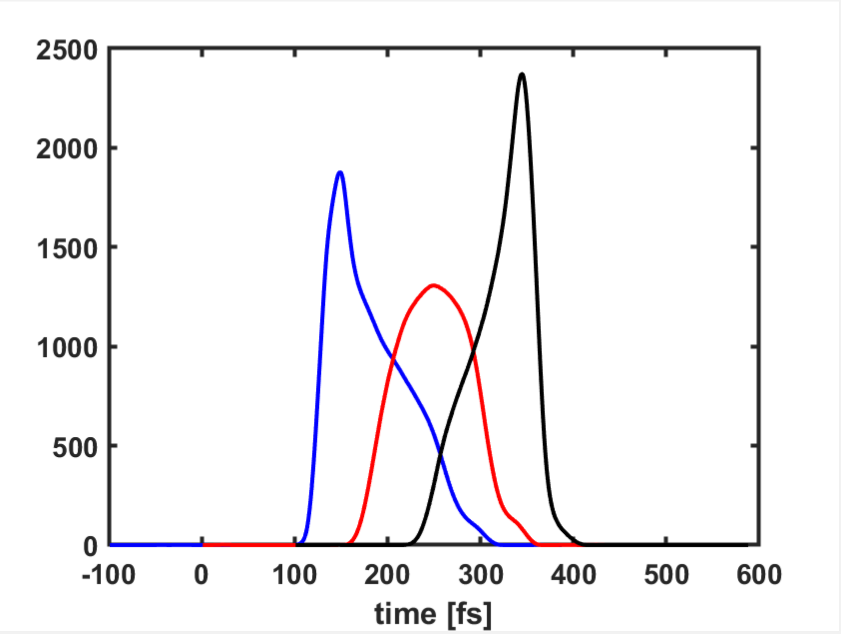
Completely compressed

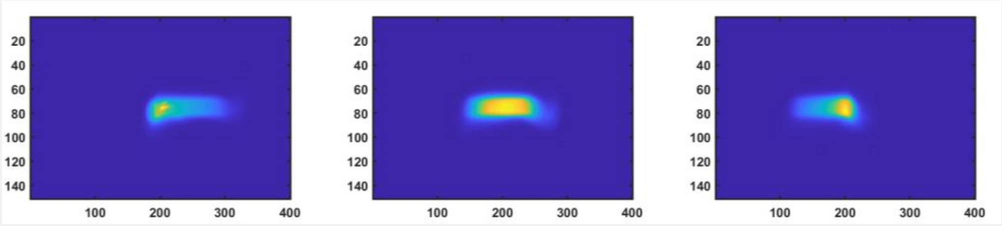
Over compressed

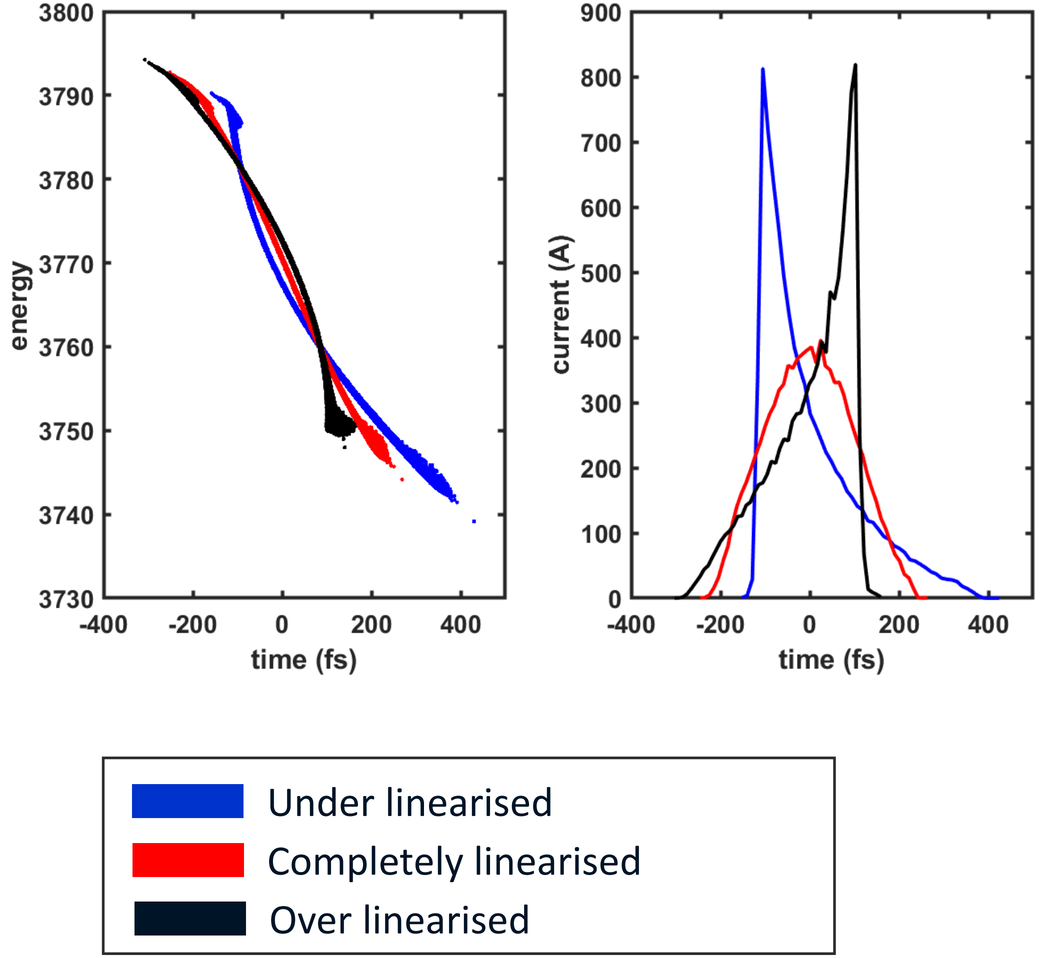
T566 scan, changing the sextupoles in BC1

Longitudinal phase space (TDC + dipole)





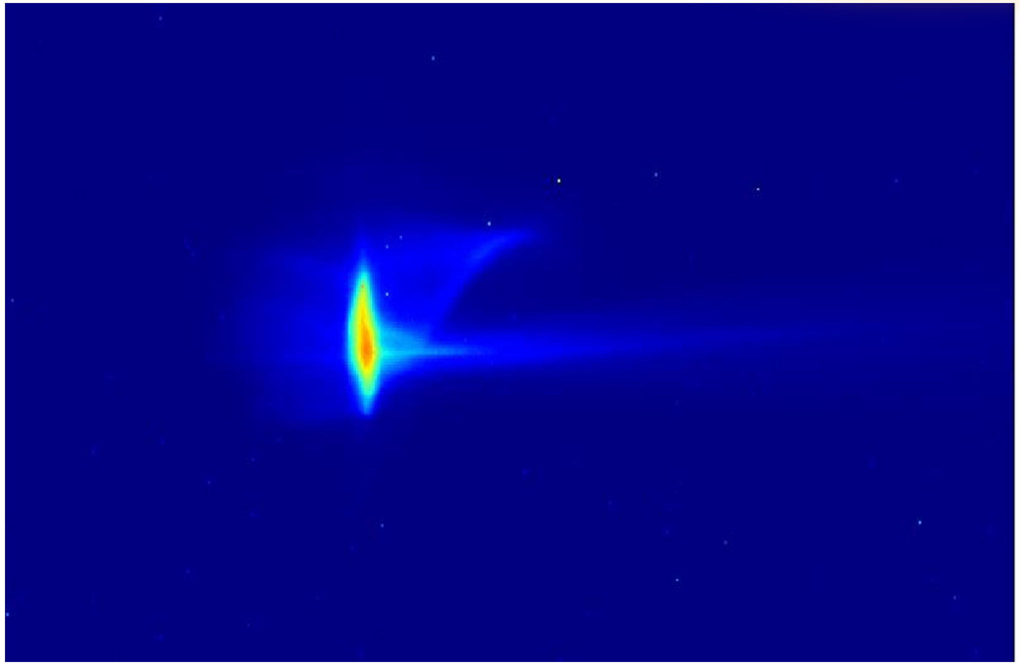


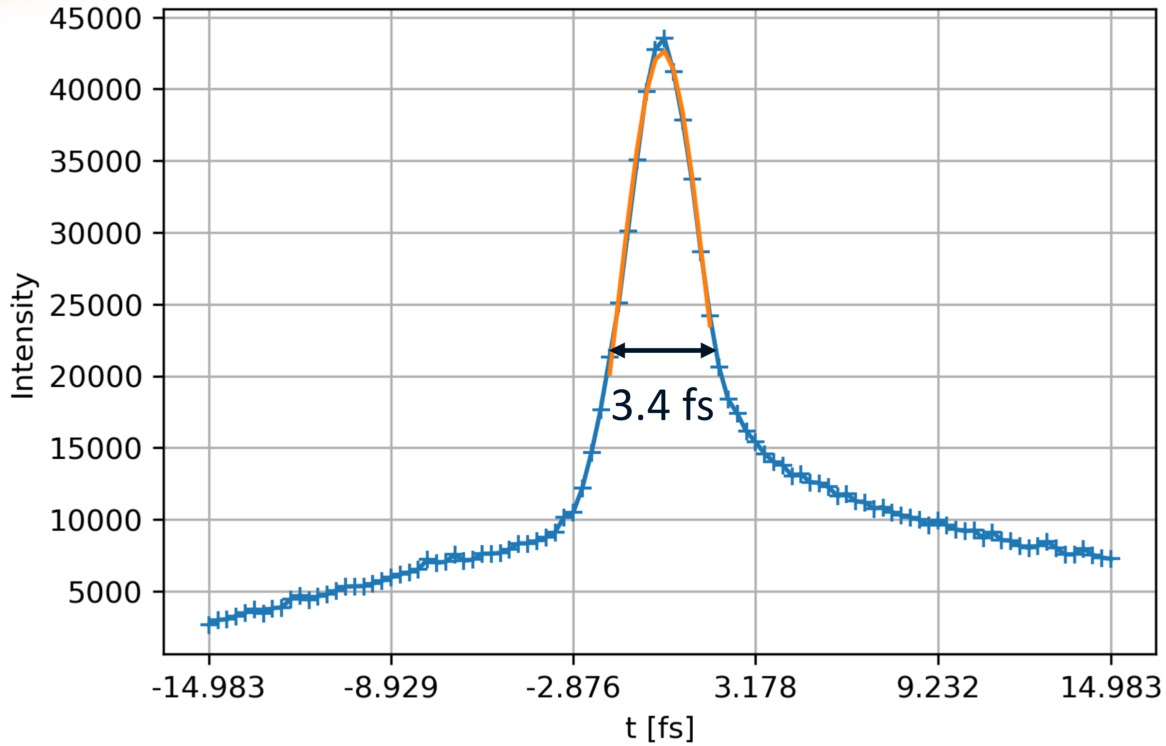


Shortest bunch measured

3.4 fs fwhm

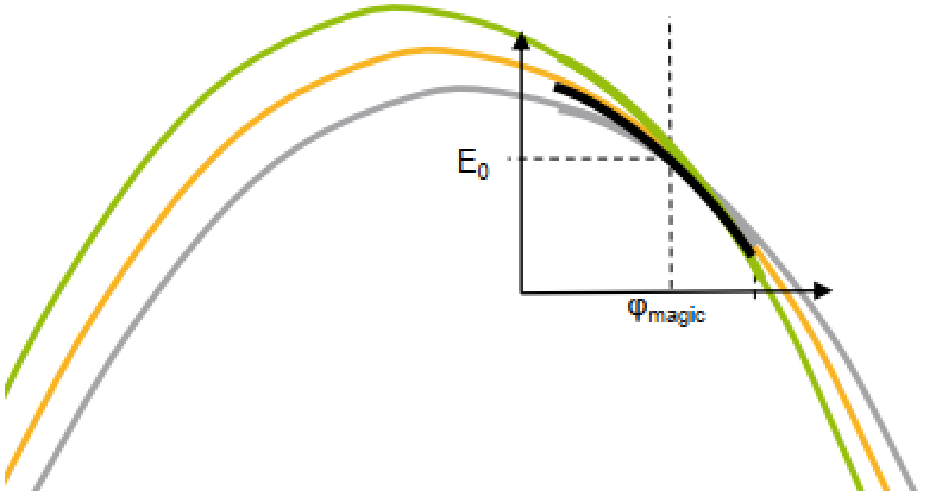
- 100 pC
- High energy spread from the gun
- Limited by TDC resolution



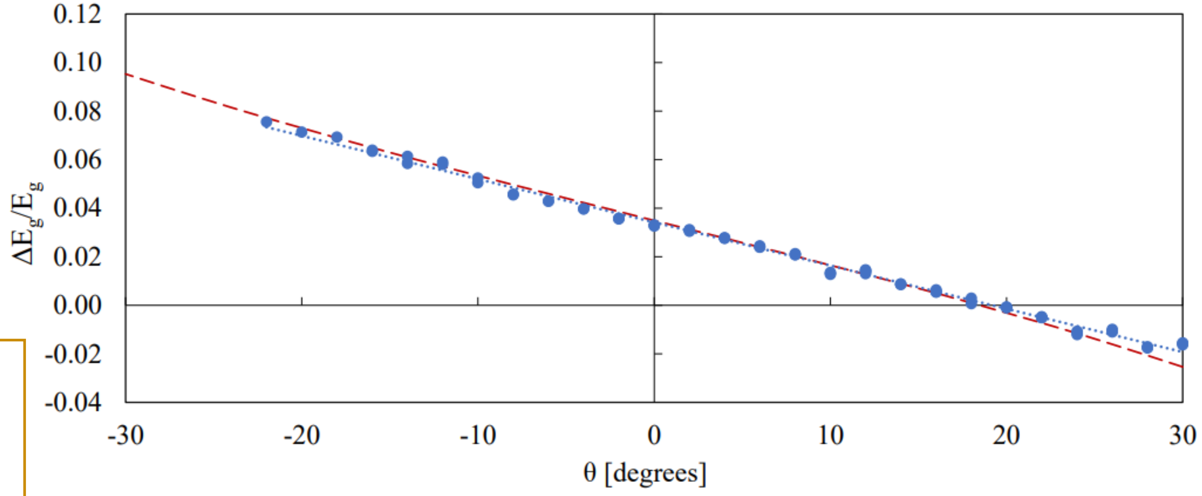


Magic angle

Mansten, Erik, et al. "Cancellation of klystron-induced energy and arrival-time variations in linear accelerators with arc-type bunch compressors." *Physical Review Accelerators and Beams* 27.4 (2024): 040401.

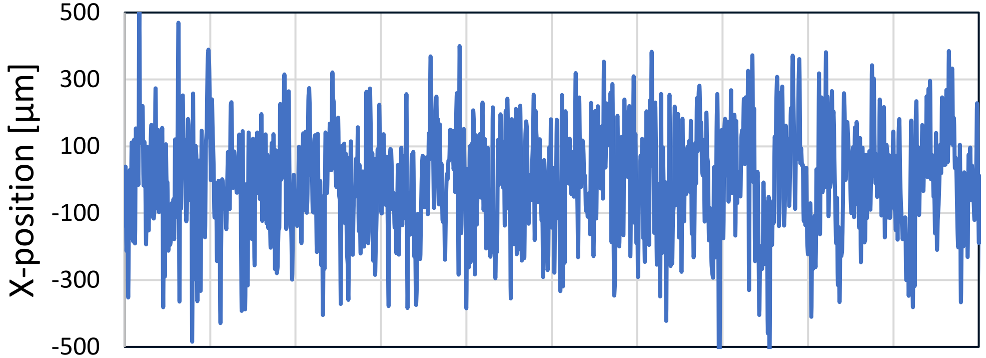


- Voltage and phase jitter from a klystron is correlated.
- Accelerating on the falling RF slope – arc like compressor
  There is a phase where the angle and voltage jitter completely cancel out.
- We can effectively reduce arrival time jitter caused by klystron HV jitter to zero.



More on temporal jitter reduction In slides from FEL presentation by Erik:
***Low-jitter conversion from optical references to electrical radio frequency signals* THAC04**

Optical master oscillator – energy stability



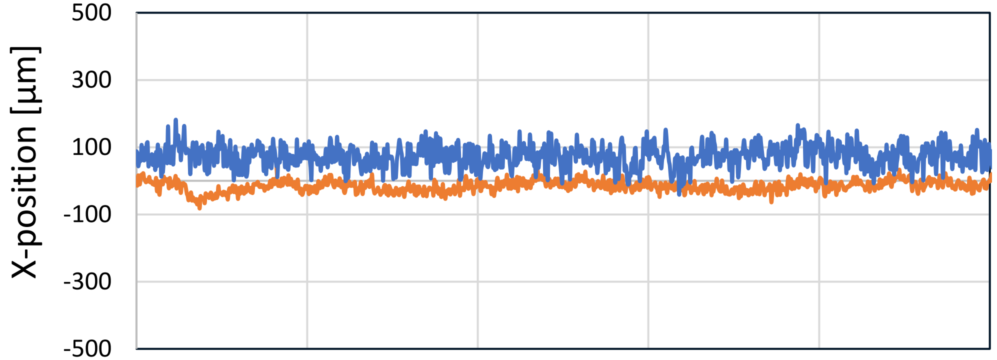
SMA100A

BC1

- 272 um RMS jitter
- 6.8e-4 energy jitter
- 38 fs - 74 fs time jitter (after BC1)

BC2

- 78 um RMS jitter
- 1.9e-4 energy jitter
- 26 fs - 84 fs (after BC2)



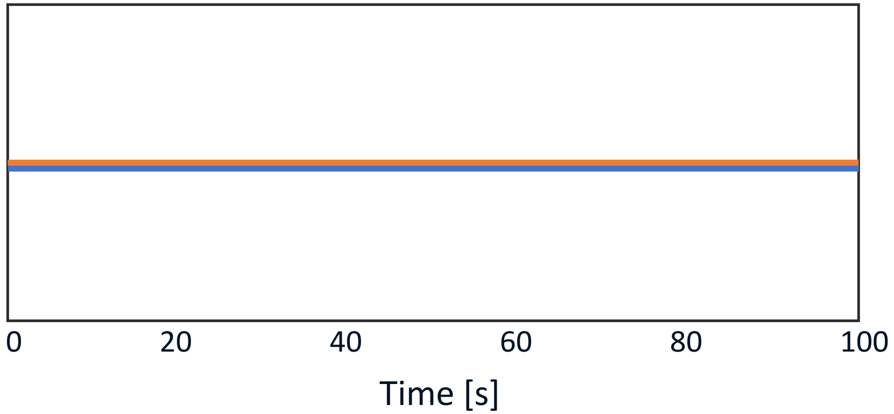
Optical MO

BC1

- 54 um RMS jitter
- 1.3e-4 energy jitter
- 7 fs – 14 fs time jitter (after BC1)

BC2

- 19 um RMS jitter
- 5e-5 energy jitter
- 5.8 fs - 17 fs (after BC2)



Optical MO – low noise fiber oscillator

- New RF reference from Quantic Wenzel
- Lower absolute phase noise fiber oscillator
- Continued fine tuning of direct RF conversion
- Stabilized fiber links
- Direct seeding

Slide by Erik Mansten

BC1_BPL01 BC2_BPL01

Arc VS Chicane compressors

Benefits of arc compression

- No church towers, horns in the head and tail of the bunch. For arc compression, the horn is in the center.
- No need for harmonic cavity **(would solve the very high frequency linearizers for C and X-band linac)**
- Linac wakes contribute to the chirp -> less off crest phase to get the same chirp -> more energy per linac section
- No emittance degradation caused by the horn radiating towards the center of the bunch – the horn from arc compression is in the center and is the lasing part of the bunch. *“We don’t have any towers irradiating our usable area because the single tower IS the usable peak which makes all the difference.”*
- No CRS hitting the bunch center from a horn means reduction in charge jitter induced energy jitter. Reduces arrival time jitter.
- Magic angle – reduces arrival time jitter.
- The arc compression technique easily produce very short pulses. Most of the accelerated bunch is within the usable center peak.

Drawbacks of arc compression

- Chromatic effects – in the current MAX IV compressors there is only one family of sextupoles – second order momentum compaction closure and linearization are not independent.

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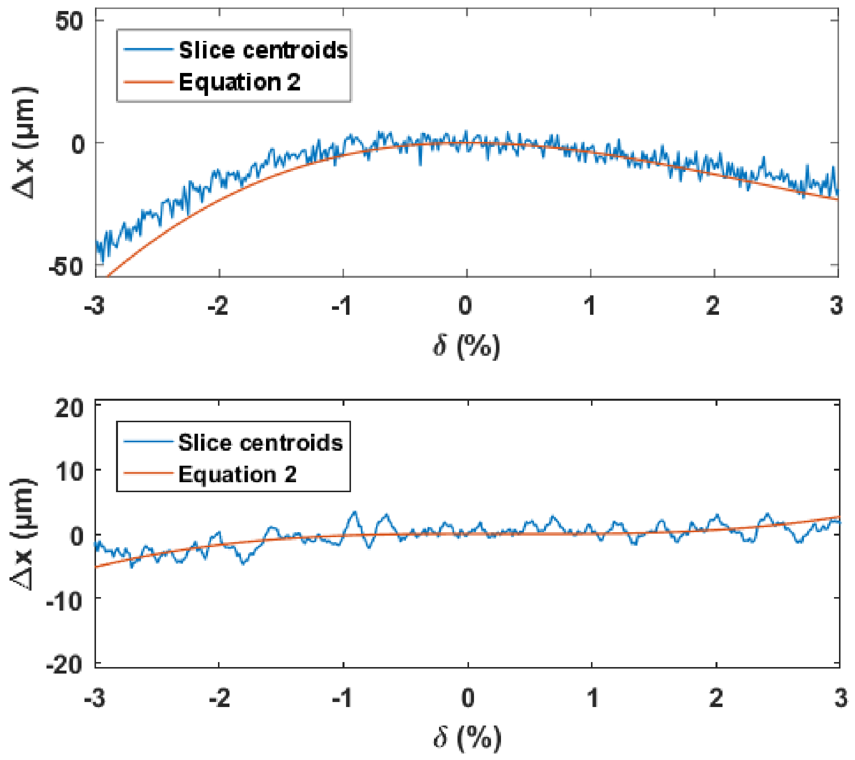
Mitigation

- Adding quads, sextupoles and possibly octupoles to compressors
- Keep longitudinal slice alpha, beta and centroid flat throughout the pulse
- Compensate for CSR-kick
- Keep longitudinal centroid slice offset low

Svensson, J. B., Charles, T. K., Lundh, O., & Thorin, S. (2019). Third-order double-achromat bunch compressors for broadband beams. *Physical Review Accelerators and Beams*, *22*(10), 104401.



Drawbacks of arc compression

- Chromatic effects – in the current MAX IV compressors there is only one family of sextupoles – second order momentum compaction closure and linearization are not independent.
- Longer and cause a translation of the beamline – BC1 moves the beam 2 meters sideways early in the tunnel, which then just gets 2 meters narrower after. It is 12 meters long in total. Second compressor doubles as beam spreader. But, yes, they are long! However, in a normal conducting linac, space is saved by needing fewer linacs, due to the linac wakes not reducing the bunch energy. Also, no need for a harmonic linac.

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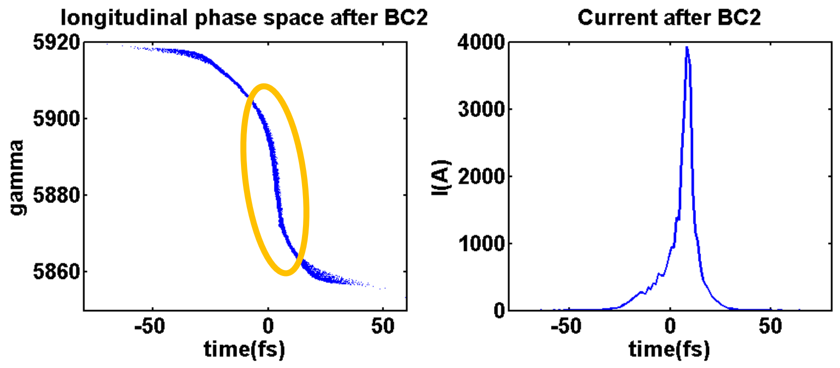
- Residual energy chirp – the wakes in the linac work towards larger chirp, not to reduce it as for chicane compressors.



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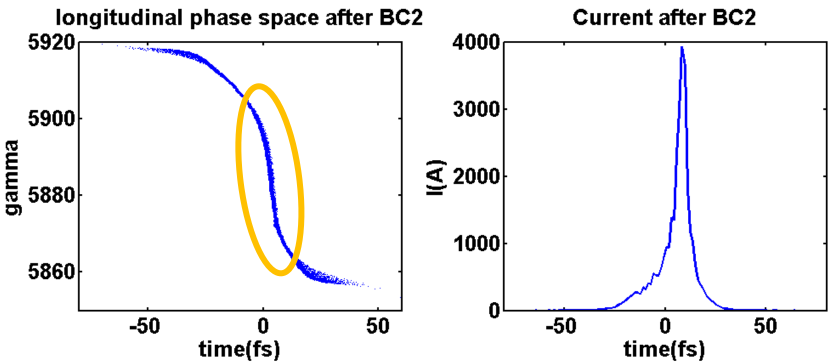
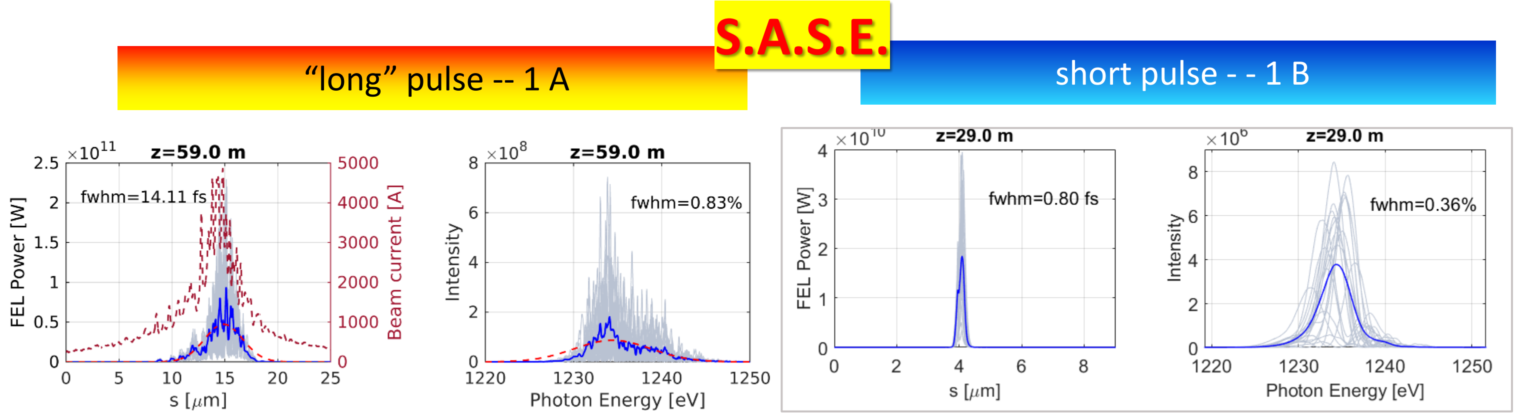




Francesca Curbis FEL chapter of SXL CDR https://www.maxiv.lu.se/beamlines-accelerators/accelerators/soft-x-ray-laser

Drawbacks of arc compression

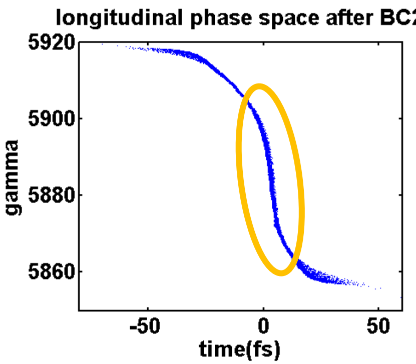
- Chromatic effects – in the current MAX IV compressors there is only one family of sextupoles – second order momentum compaction closure and linearization are not independent.
- Longer and cause a translation of the beamline – BC1 moves the beam 2 meters sideways early in the tunnel, which then just gets 2 meters narrower after. It is 12 meters long in total. Second compressor doubles as beam spreader. But, yes, they are long!
- Residual energy chirp – the wakes in the linac work towards larger chirp, not to reduce it as for chicane compressors. Not a big problem for SASE.

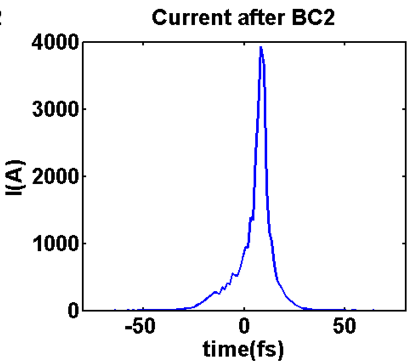
How about seeding? Needs flat area.

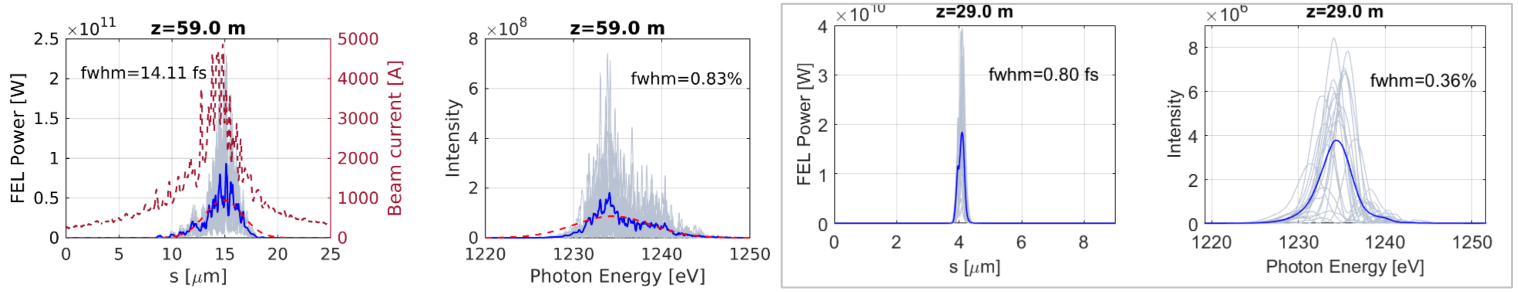
“long” pulse -- 1 A

S.A.S.E.

short pulse - - 1 B







Francesca Curbis FEL chapter of SXL CDR https://www.maxiv.lu.se/beamlines-accelerators/accelerators/soft-x-ray-laser

De-chirping may be possible with dielectric waveguide – or by using variable bunchcompressors!

Variable R56 in the arc compressors

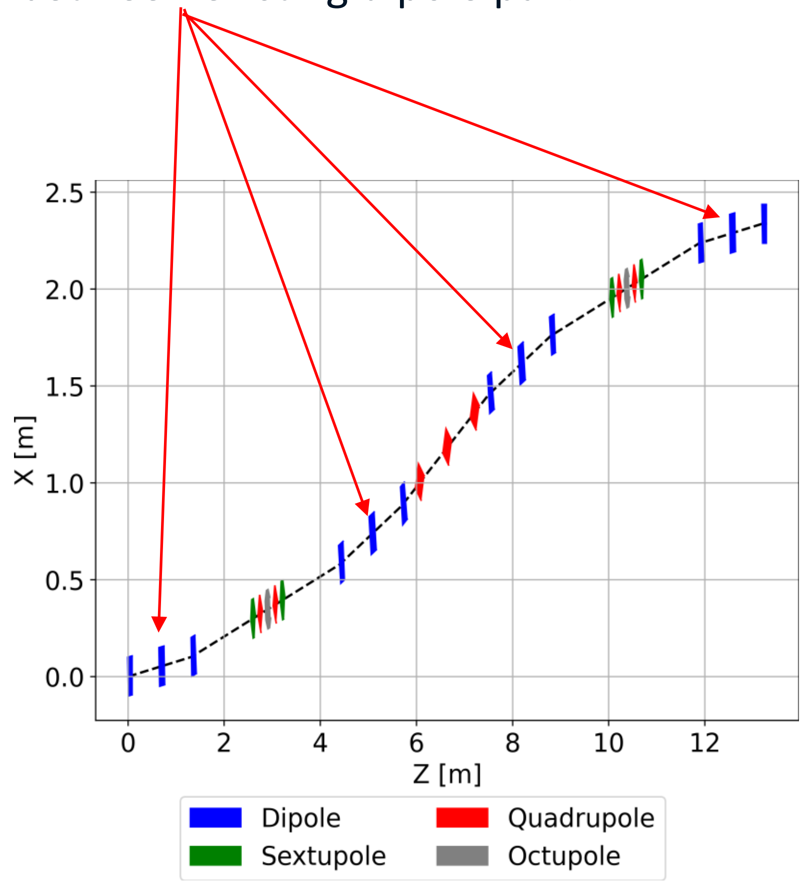
R_{56} variability can be achieved with additional dipoles placed between the existing dipole pairs

*(P. H. Williams, G. Pérez-Segurana, I. R. Bailey, S. Thorin, B. Kyle, and J. B. Svensson, **Arclike variable bunch compressors**, Physical Review Accelerators and Beams 23, 100701 (2020).)*

*(Adam Dixon, et al. **Reduction of arrival time jitter or energy spread with arclike variable bunch compressors**, to be published)*

- Finetuning of compression – don't depend only on phase to optimize
- Allows us to operate at the magic angle – decreasing arrival time jitter

Additional dipoles
placed between existing dipole pair.



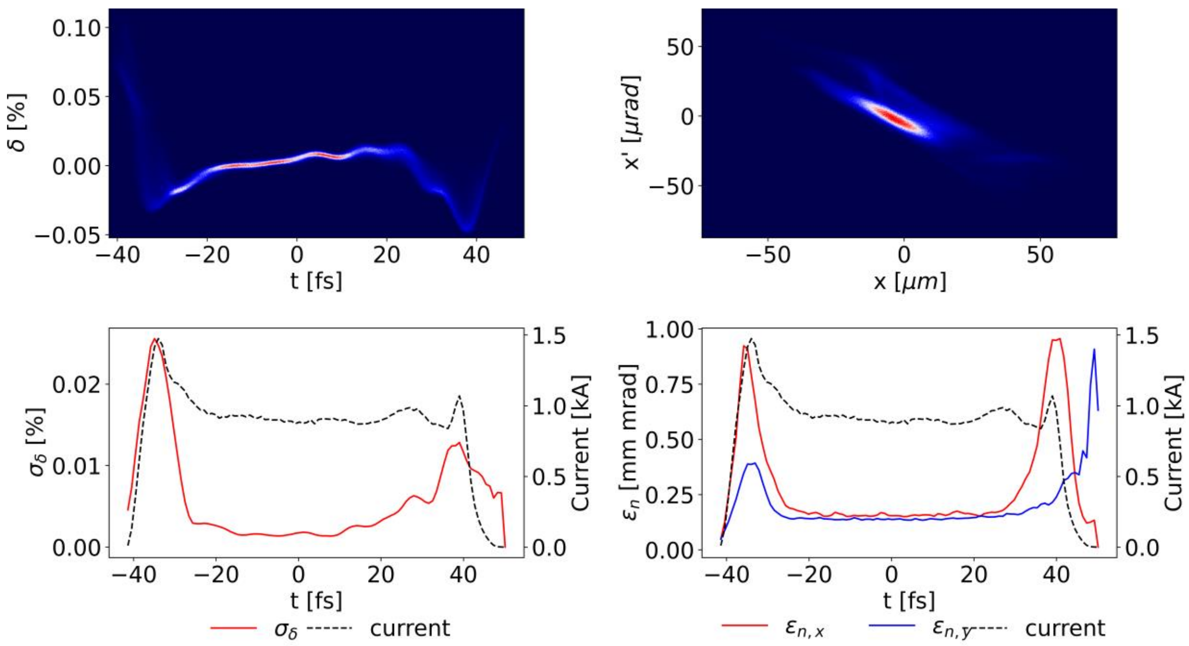
Variable R56 in the arc compressors

R_{56} variability can be achieved with additional dipoles placed between the existing dipole pairs

(P. H. Williams, G. Pérez-Segurana, I. R. Bailey, S. Thorin, B. Kyle, and J. B. Svensson, ***Arclike variable bunch compressors****, Physical Review Accelerators and Beams 23, 100701 (2020).)*

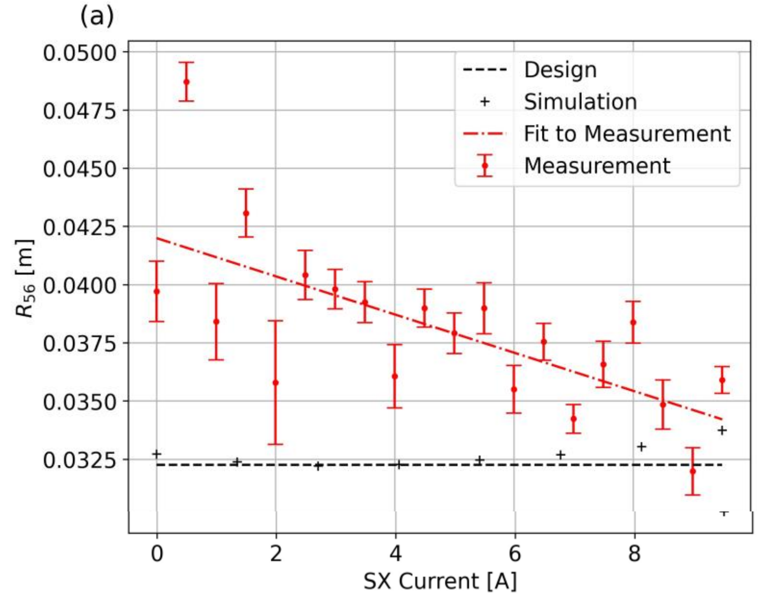
(Adam Dixon, et al. ***Reduction of arrival time jitter or energy spread with arclike variable bunch compressors****, to be published)*

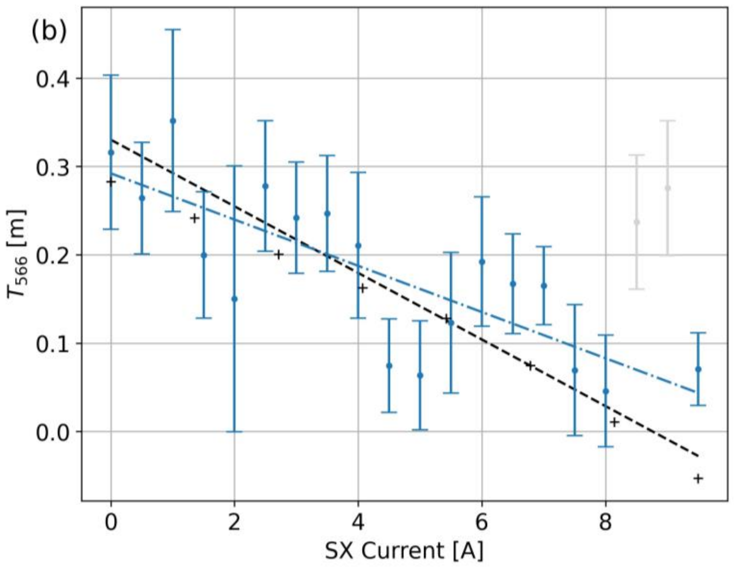
- Finetuning of compression – don't depend only on phase to optimize
- Allows us to operate at the magic angle – decreasing arrival time jitter
- These compressors could be tuned to R56=0 and even R56<0 mimic chicane compression to get de-chirping in the main linac – reduce the energy chirp.



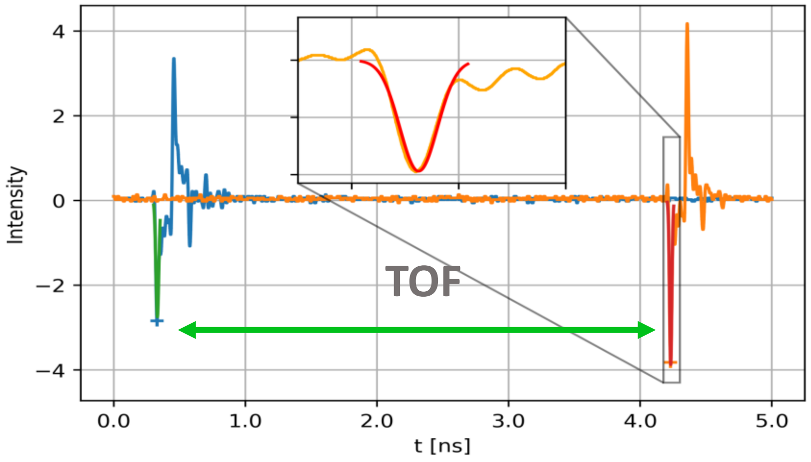
Recent experiments using the MAX IV compressors

Measuring R56 and T566 in BC1





Simulation
R56:0.032±0.000, T566:0.113±0.001
Measurement
R56:0.040±0.001, T566:0.138±0.081

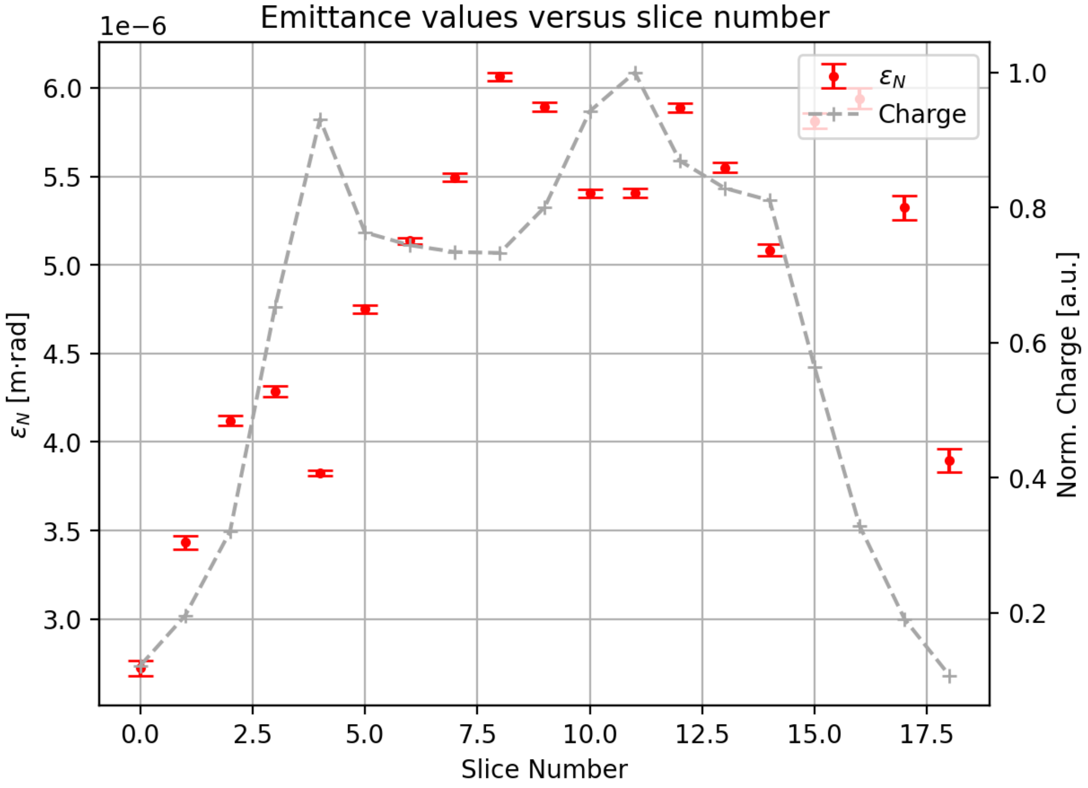


Johan Lundquist *Measurement of First and Second Order Longitudinal Dispersion in the MAX IV Bunch Compressor* **TUP006 FEL 2024**

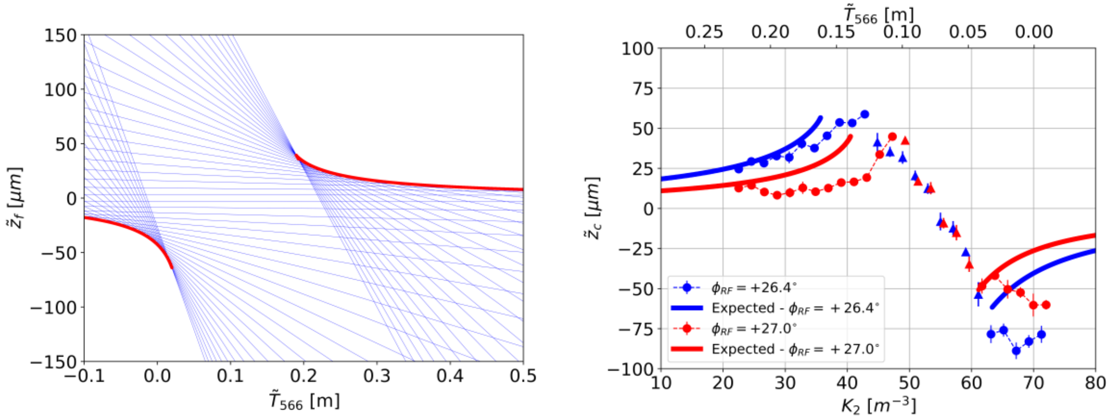
Using a BPM channel before and after BC1 and measuring TPF difference for two different energies.

Recent experimental work with the TDC

Johan Lundquist slice emittance measurements using the TDC.



Adam Dixon *Measurements of Particle Trajectory Caustics in Bunch Compressors* **TUP090 FEL 2024**



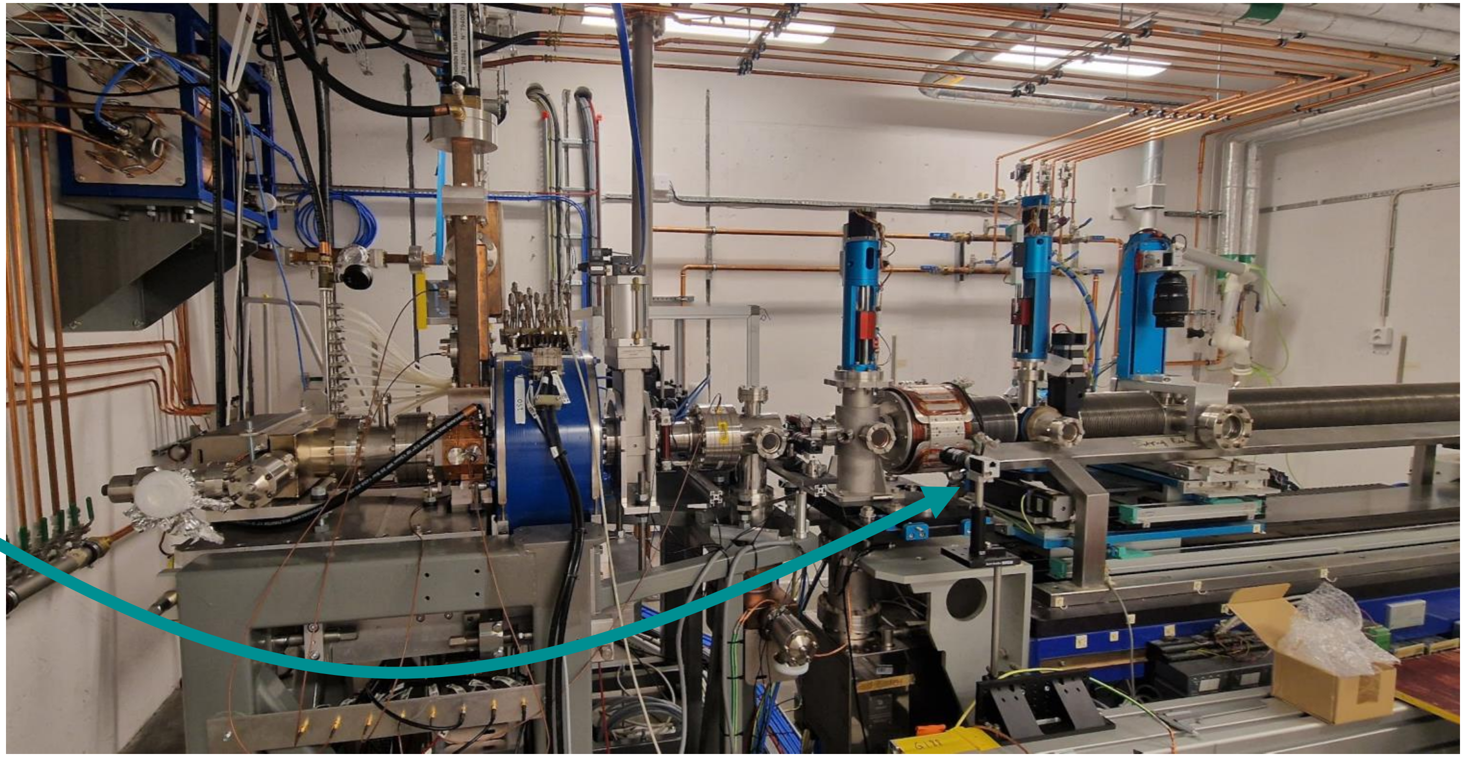
Trajectories of final longitudinal position of an electron in a bunch as function of second-order longitudinal dispersion.

Current spike development is sensitive to small changes in the initial longitudinal phase space distribution and longitudinal dispersion Sharp current spikes emit strong CSR, increases emittance and energy spread/**is the actual usable part of the bunch.**

T. K. Charles et al."Caustic-based approach to understanding bunching dynamics and current spike formation in particle bunches," Phys. Rev. AB,, 2016.

Gun test facility

- Finally operational
- Operate with SLED
- 10 Hz
- Very old but functioning solenoid
- Emittance meter from Frascati – refurbished and working well
- Permit to operate at 100 Hz in progress
- Spectrometer dipole – next step.



Open positions at MAX IV

50-100 pmrad emittance, start of dark period July 2029, first light to users September 2030

Magnet engineer – design and implementation of new magnets for MAX 4U, system owner of all magnets at MAX IV.

Post Doc Collective effects – who will work on collective effects in the MAX 4U upgrade project as well as on the existing MAX IV storage rings.

Post Doc Longitudinal Injection – Injection schemes to inject a ring with very small dynamic aperture. *(advert coming soon)*

https://www.maxiv.lu.se/about-us/careers/vacancies/

Summary

- MAX IV have been successfully operating arc compressors for 10 years.
- Recent addition of a TDC has allowed full diagnostics of LPS and results look very promising and follow expectations.
- TDC temporal resolution ~3fs fwhm so far. Beam focus and RF poer is work in progress to improve resolution.
- The main benefits of arc compression include:
  - energy saving due to not loosing energy to linac wakes
  - no need for harmonic cavity
  - no emittance degradation caused by high current horns
  - reduced energy jitter/arrival time jitter due to the magic angle and charge depended CSR irradiation
- The main drawbacks of arc compressors are:
  - chromaticity – needs careful optics design to compensate
  - Correlated energy spread – doesn't matter for all FEL modes, arcs can be made with variable R56 to create a flat energy electron distribution.

Acknowledgement

- Mikael Eriksson, Erik Mansten and the linac team @ MAX IV
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- Francesca Curbis, Johan Lundquist, Sverker Werin, Jonas Björklund Svensson (MAX IV, Lund University)
- Tessa Charles (Australian Synchrotron)
- Gustavo Perez-Segurana (Cern)

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