

Chicane or arc compressors for FEL?

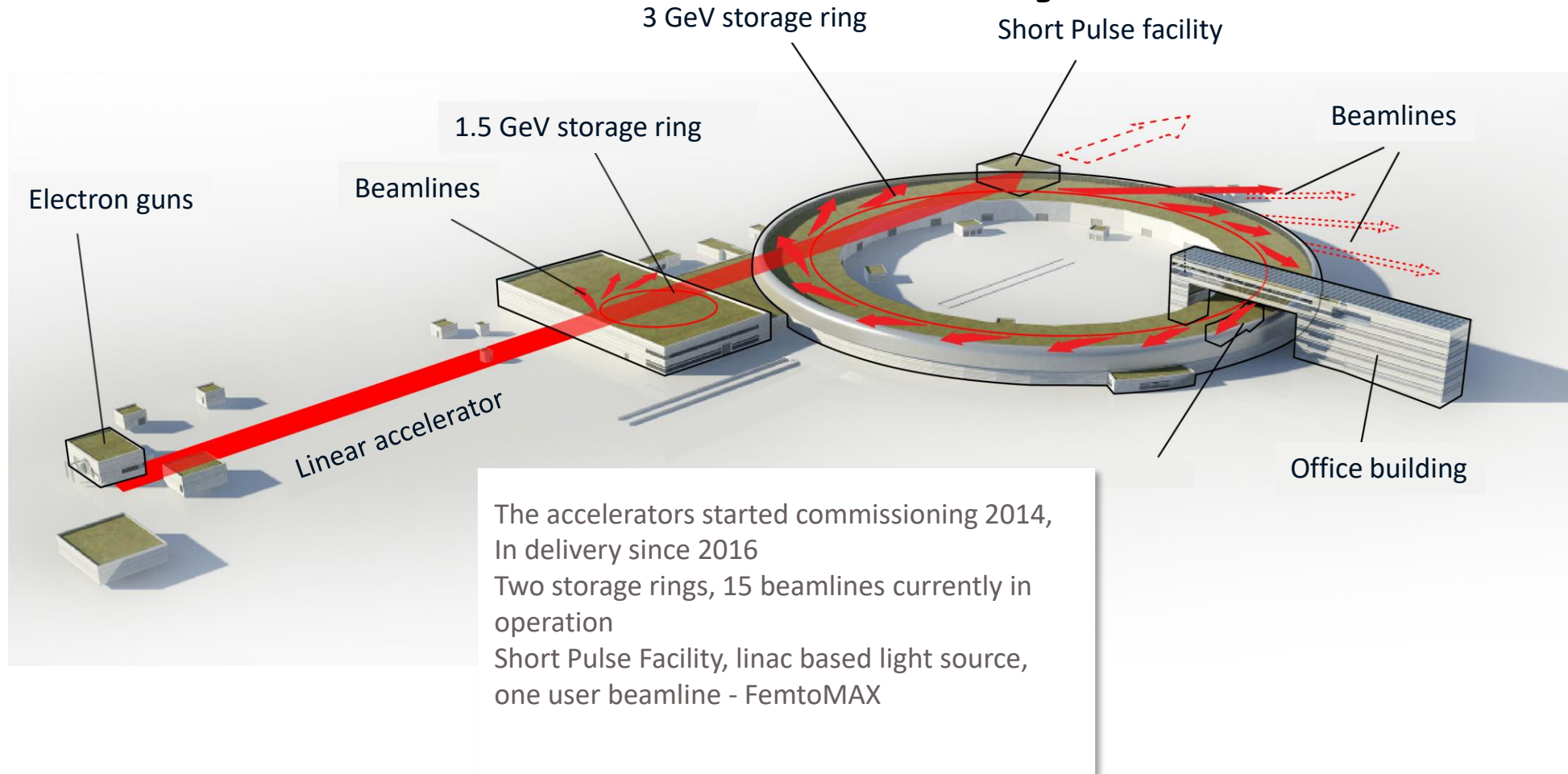
- Experience with the MAX IV arc compressors and beyond

Sara Thorin

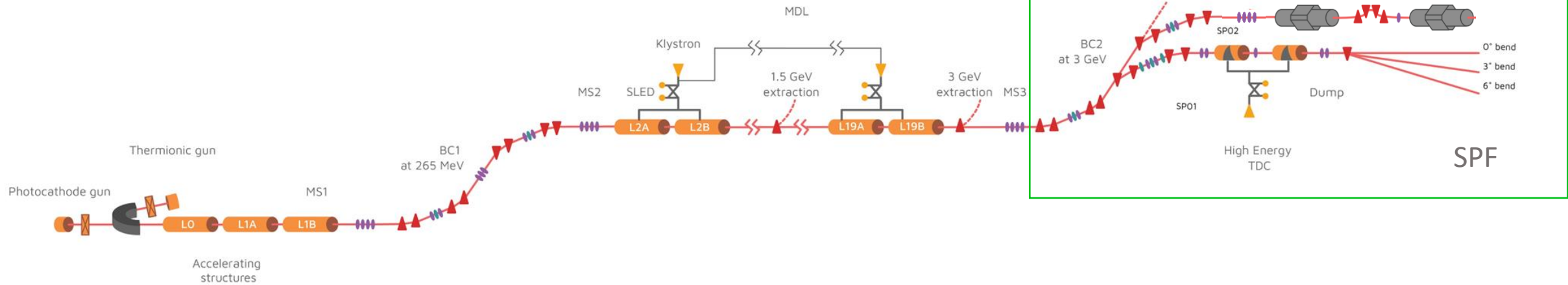
Overview of talk

- Introduction of MAX IV
- MAX IV arc compressors - design, experience and results
- Are arcs simply better? Comparison to chicane compressors
- Experimental work – interesting measurements on the compressors using the TDC

Introduction – MAX IV facility



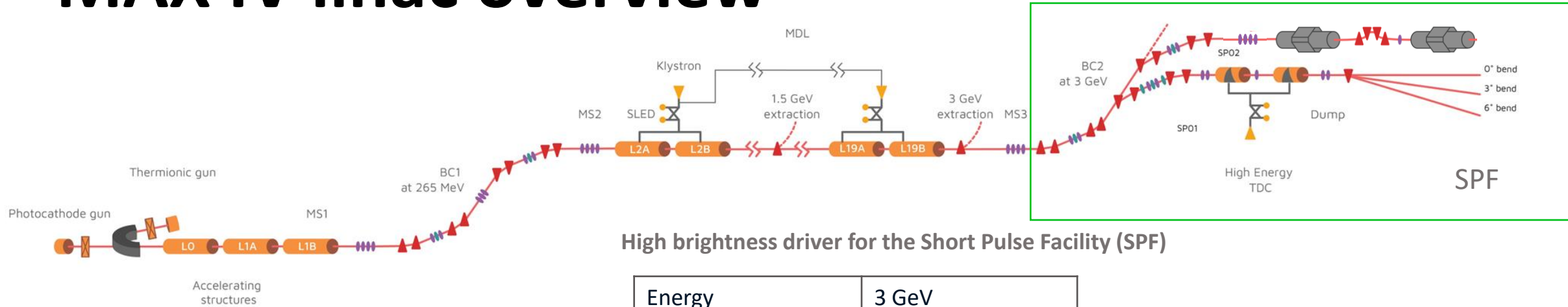
MAX IV linac overview



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



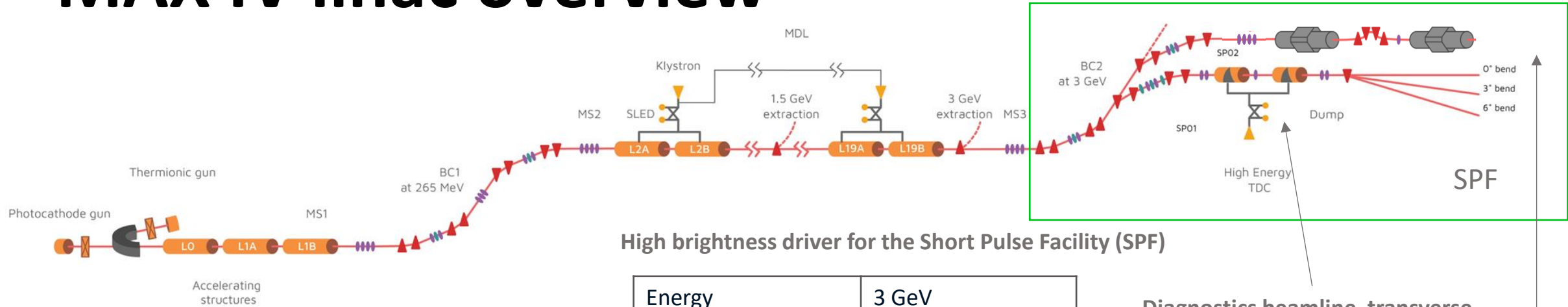
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High brightness driver for the Short Pulse Facility (SPF)

Energy	3 GeV
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Charge	20-200 pC
Bunch length (rms)	3 ps – 30 fs
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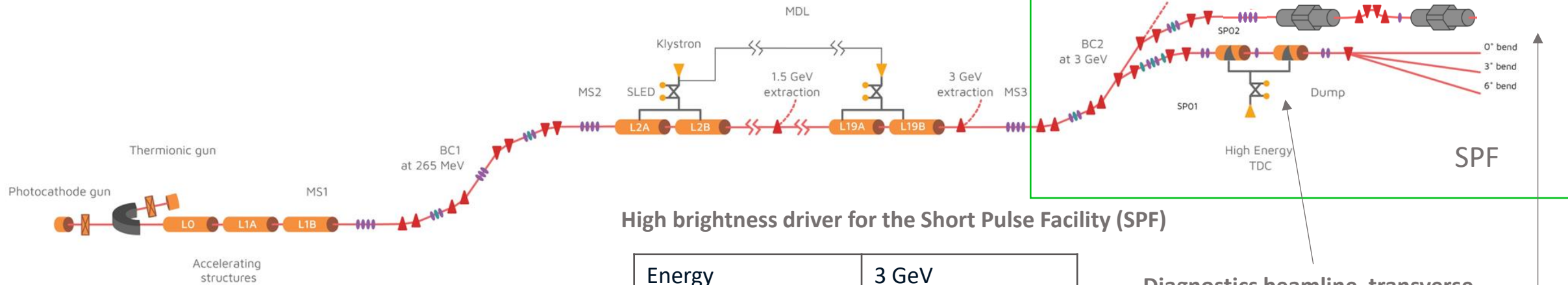
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Diagnostics beamline, transverse deflecting cavity (TDC)

FemtoMAX beamline
Ultrafast processes in solids and liquids

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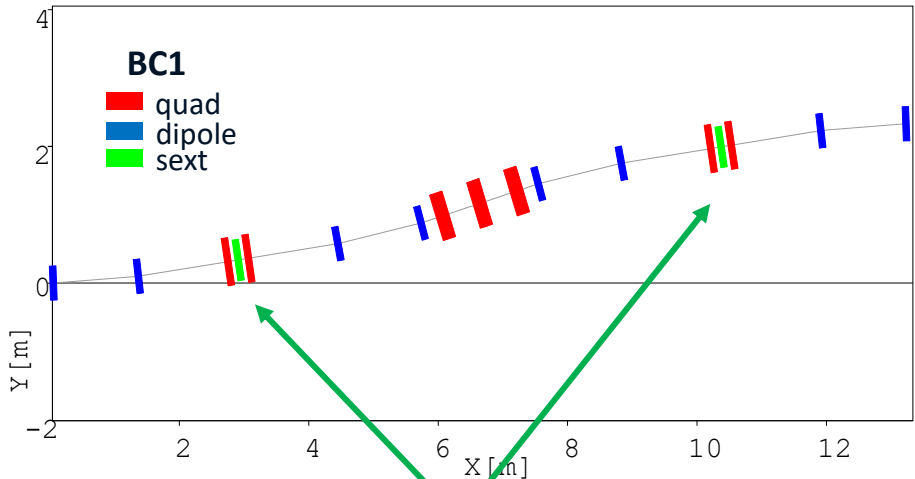
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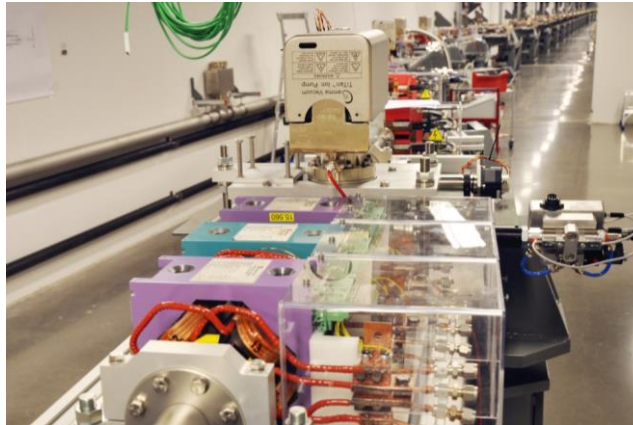
MAX IV achromat arc bunch compressors

MAX IV bunch compressors – double achromats with magnetic linearisation



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

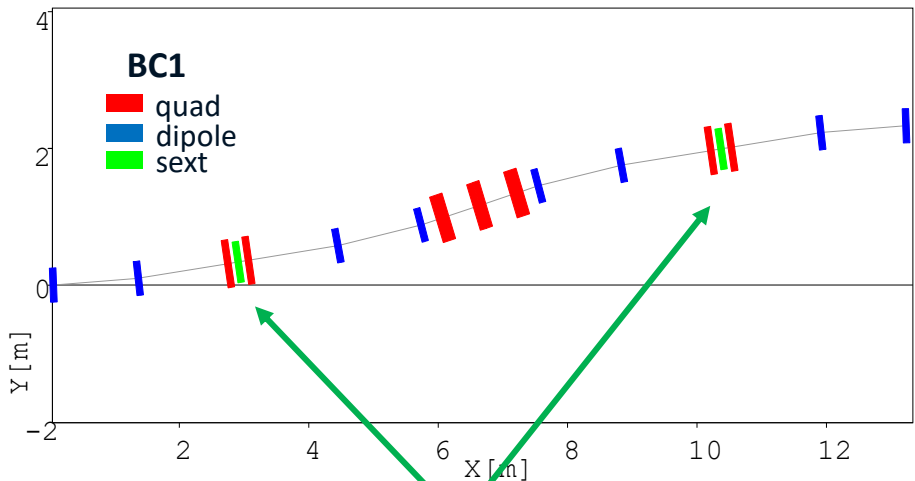
$$\Delta z = R_{56} \left(\frac{\Delta E}{E} \right) + T_{566} \left(\frac{\Delta E}{E} \right)^2$$



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

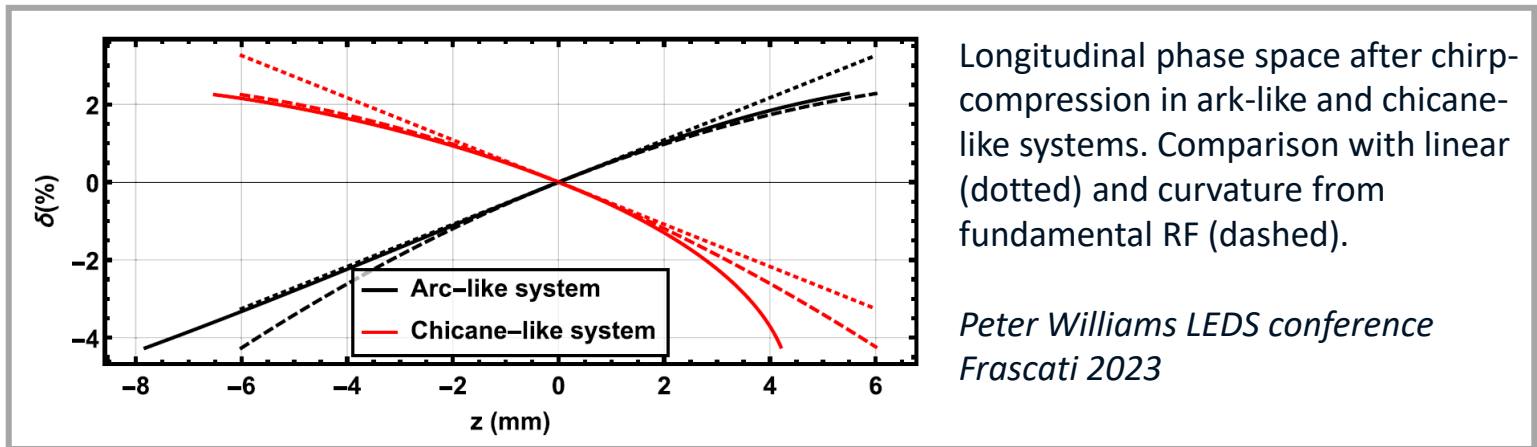
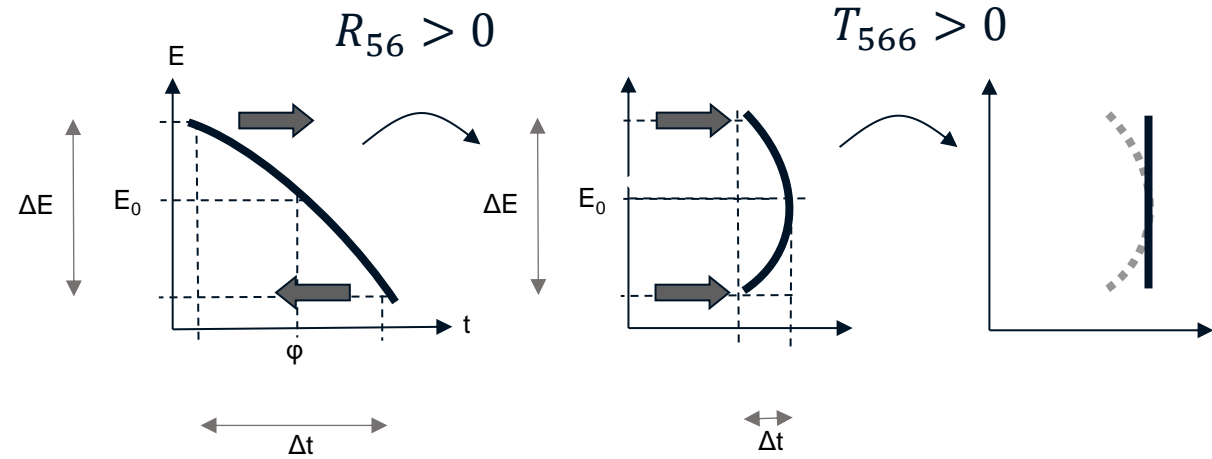
Second order momentum compaction naturally compensates for fundamental RF curvature. The linearization effect is fine-tuned with weak sextupoles.

MAX IV bunch compressors – double achromats with magnetic linearisation



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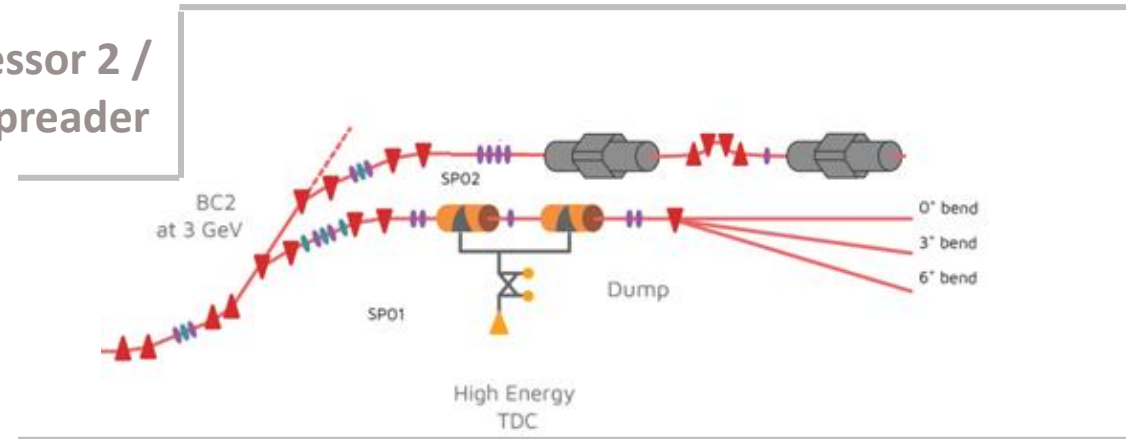
Peter Williams LECS conference Frascati 2023

MAX IV bunch compressors – double achromats with magnetic linearisation

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.

Compressor 2 /
Beam spreader

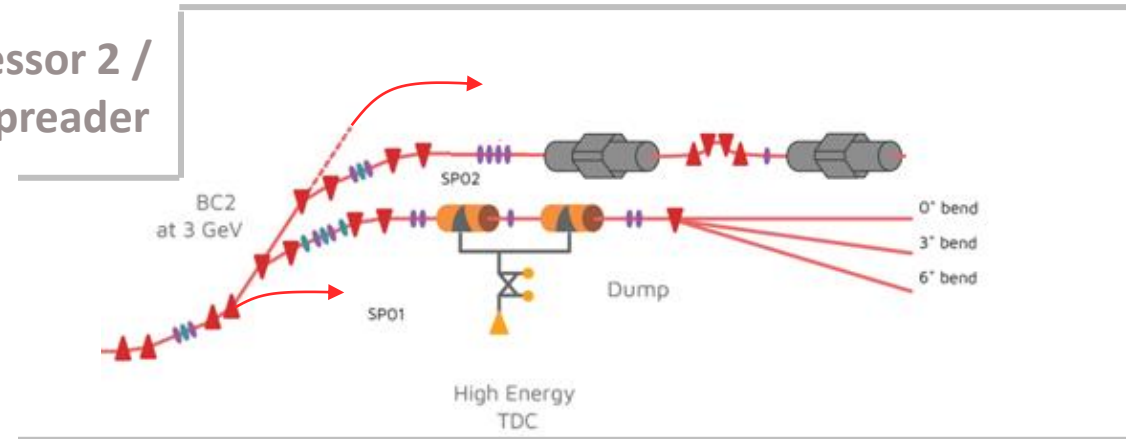


MAX IV bunch compressors – double achromats with magnetic linearisation

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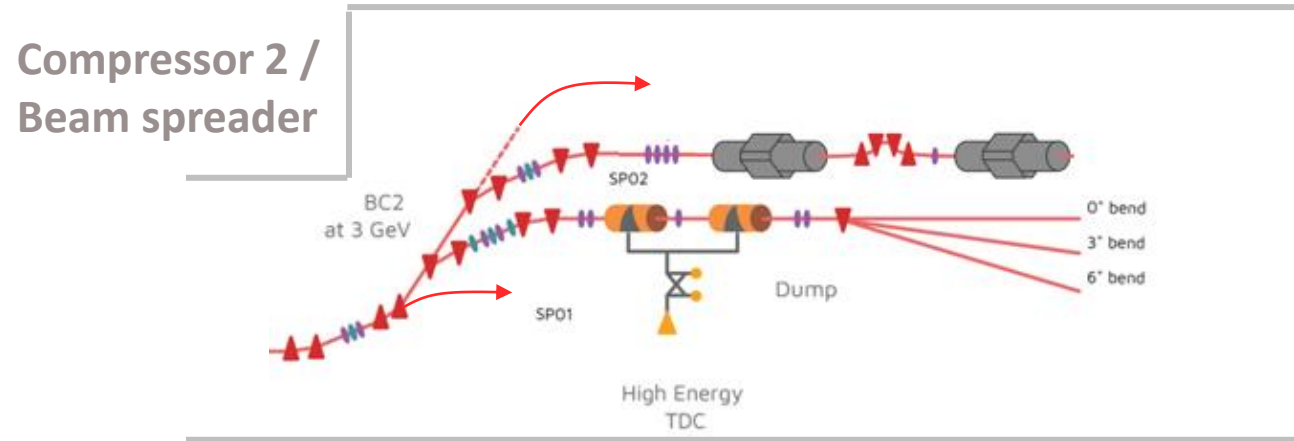


MAX IV

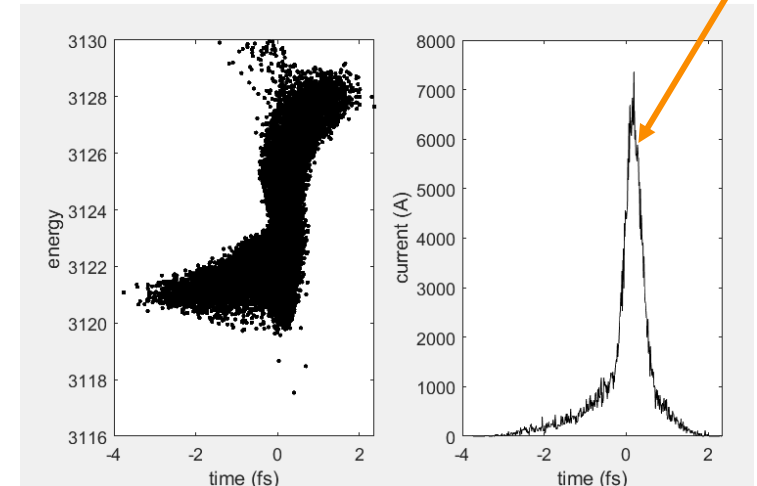
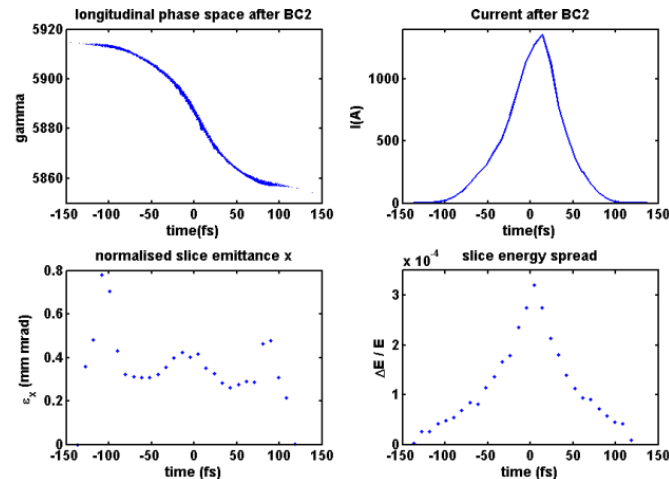
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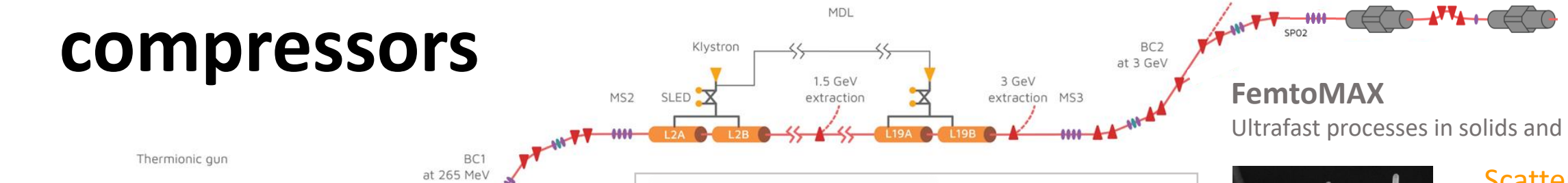
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 - Economy
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- BC2 works as beam spreader
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 - Diagnostic beamline with a TDC
- Way to give MAX IV capabilities for short pulses and a future FEL that was both cost efficient and transparent to injection.
- Potential to make very short pulses



500 as fwhm



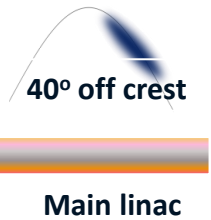
10 years of experience with the arc compressors



FemtoMAX

Ultrafast processes in solids and liquids

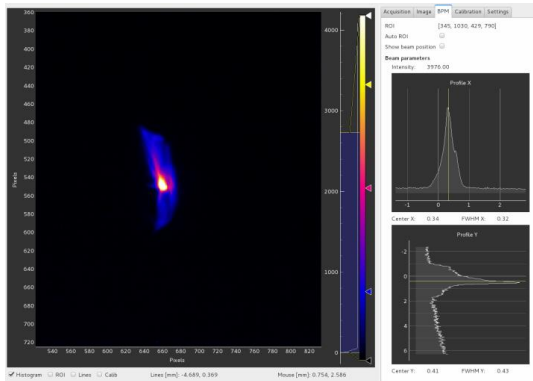
Beam compressed in BC1



Screen at maximum dispersion BC2

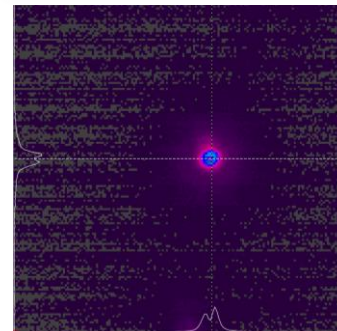
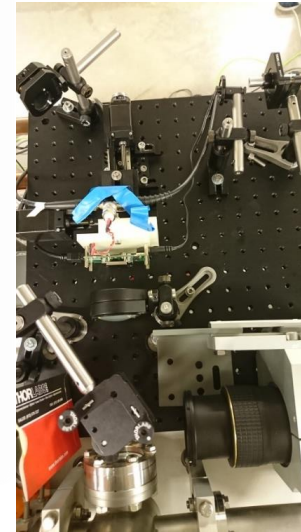
Using BC2 and linac as streak camera

- Resolution around 30 fs
- Could only measure bunch length after BC1



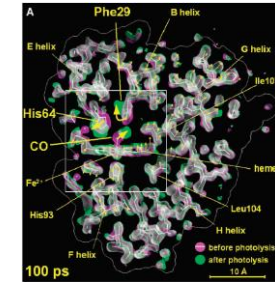
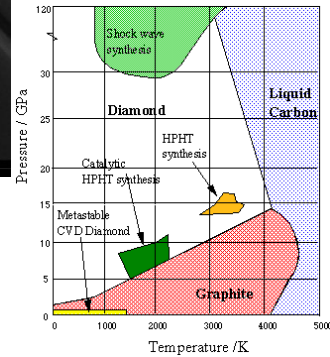
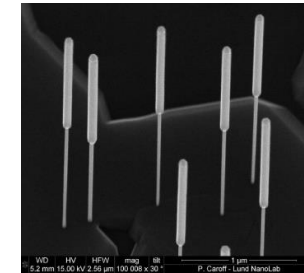
Coherent transition radiation monitor

- 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.

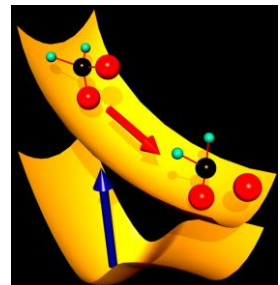


In collaboration with J. Wolfenden, T. Pacey, R. Fiorito and C. Welsch – Cockcroft Institute

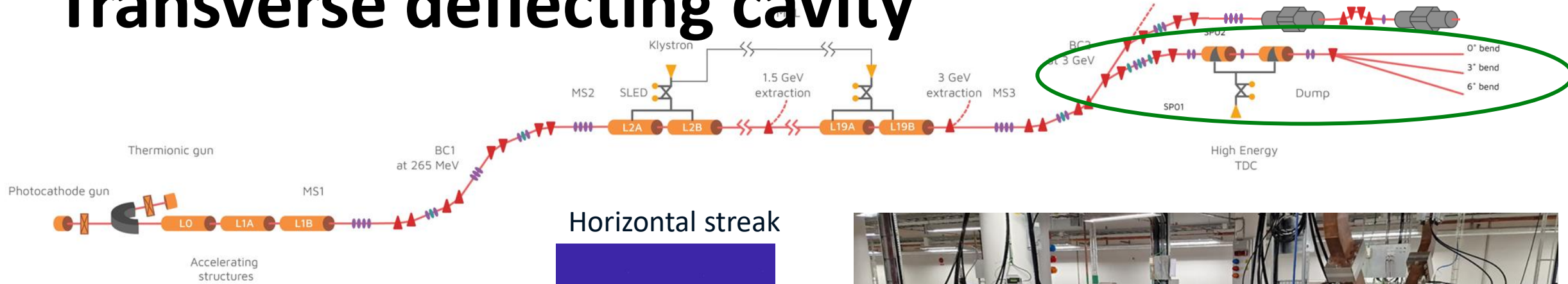
Scattering



Spectroscopy

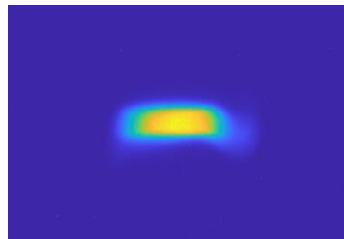


Transverse deflecting cavity

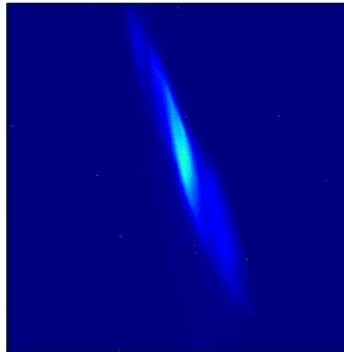


- Commissioning started during 2023
- Reached ~ 60% of full RF power
- 1 fs resolution target – reached 3 fs
- S-band (3 GHz)
- 100 MV integrated field
- Long setup
- Spectrometer dipole

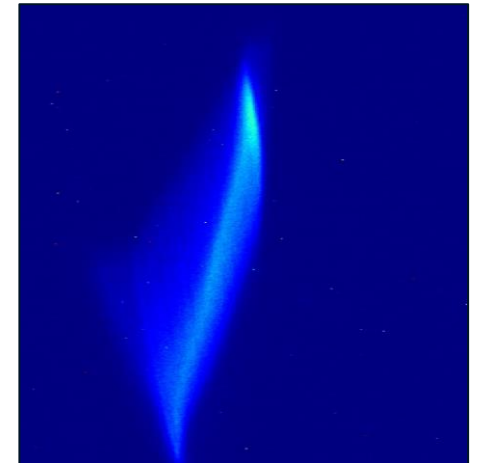
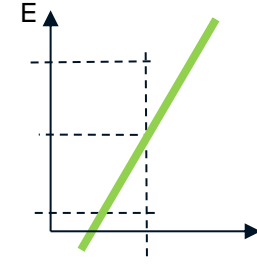
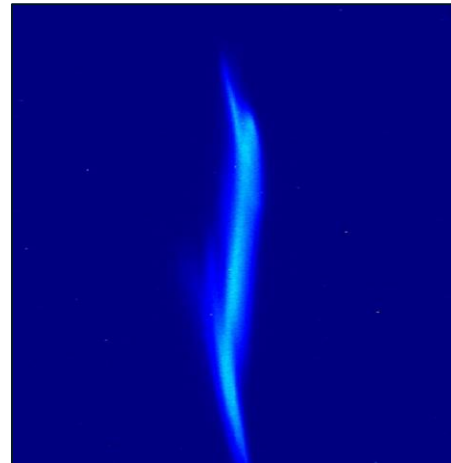
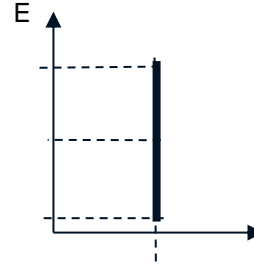
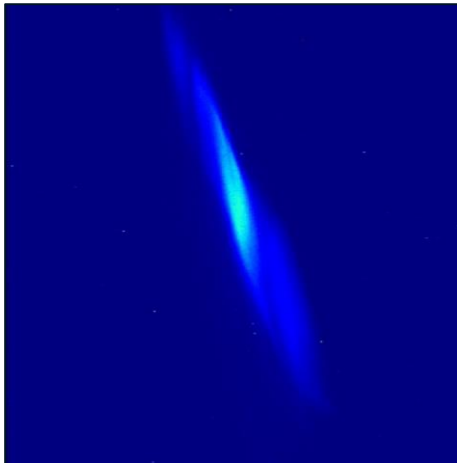
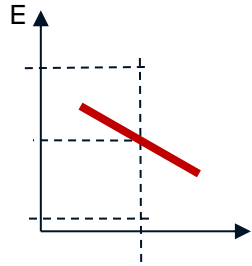
Horizontal streak



Longitudinal phase space

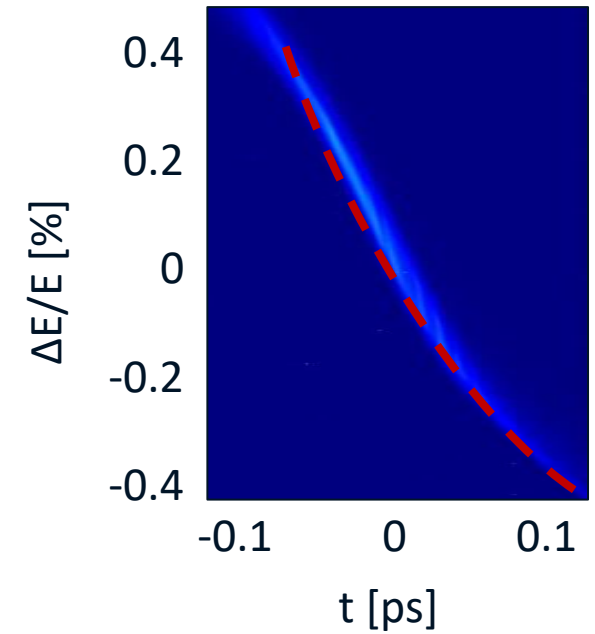
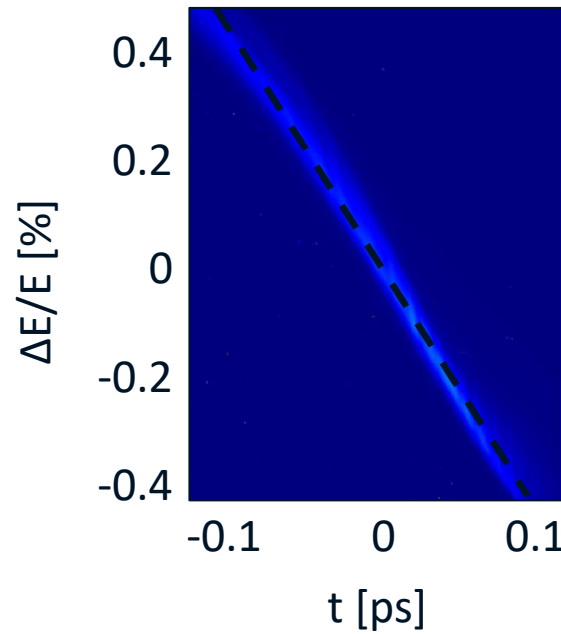
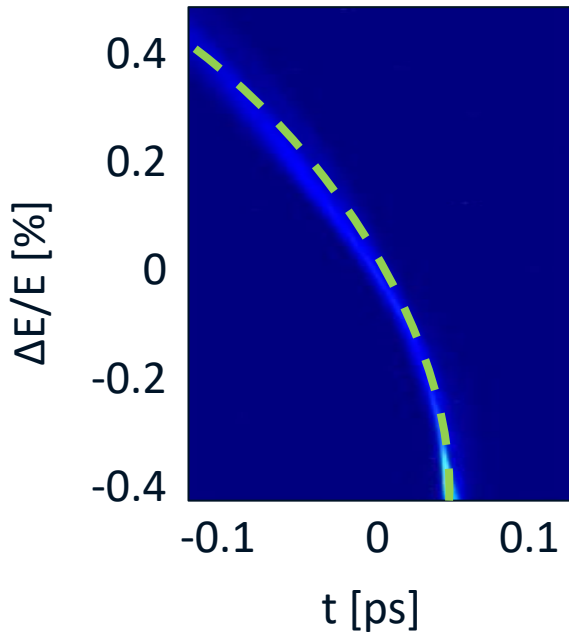
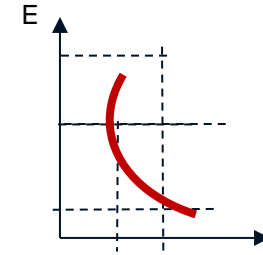
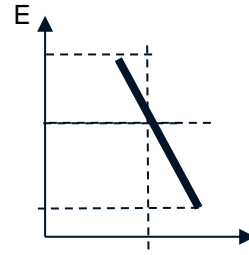
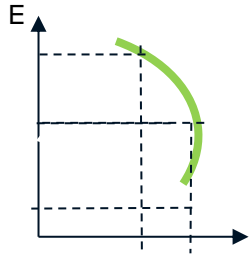


Compression scan – longitudinal phase space



Slide from Erik Mansten, Johan Lundqvist

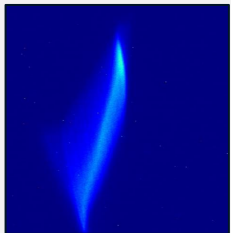
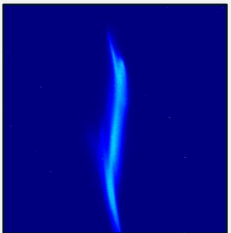
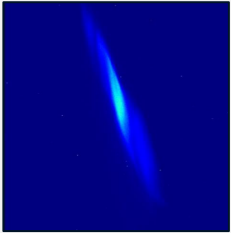
Linearization scan – Longitudinal phase space



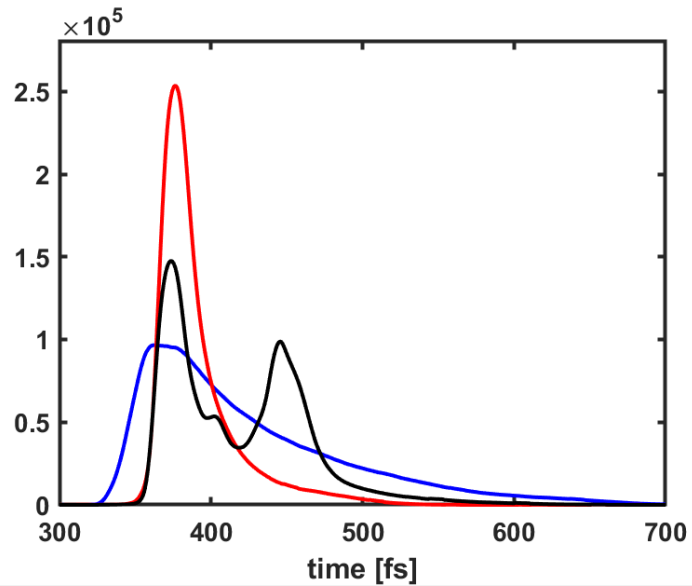
Slide from Erik Mansten, Johan Lundqvist

Compression scan – changing the phase before BC1

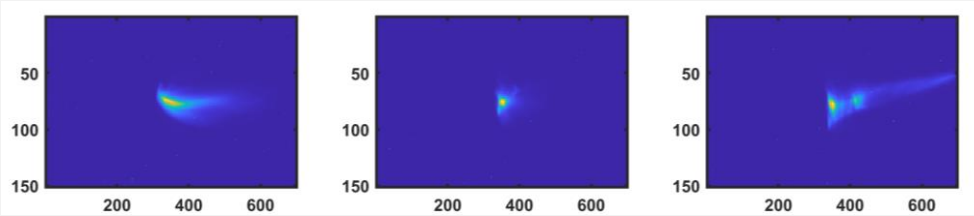
Longitudinal phase space (TDC + dipole)



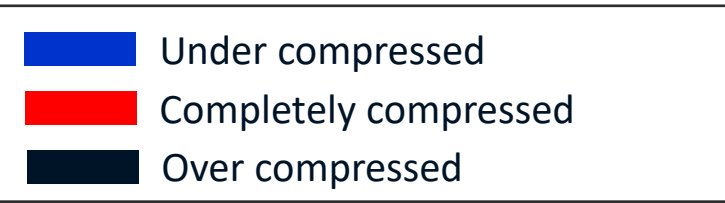
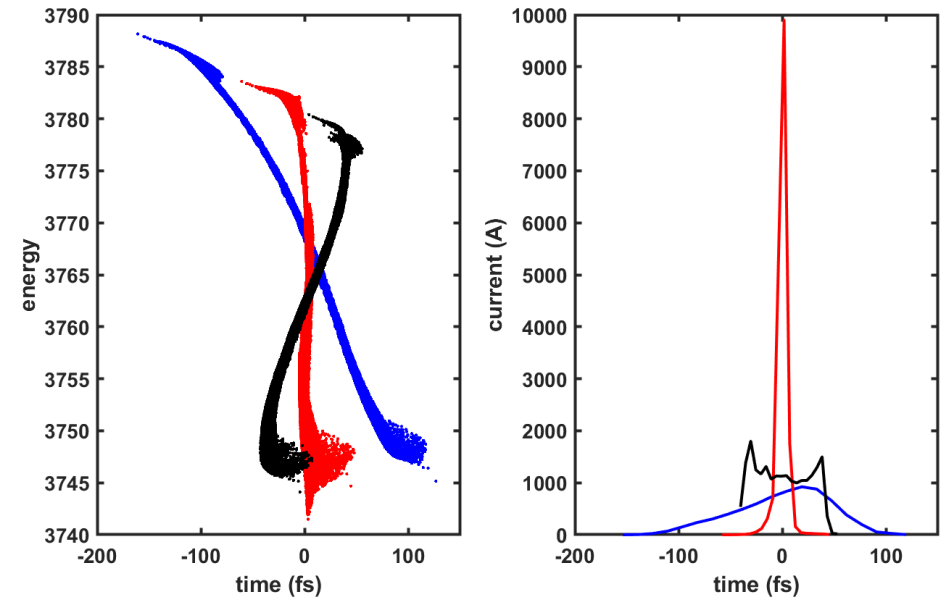
Measured electron beam at TDC after BC2



Longitudinal phase space (TDC streak)

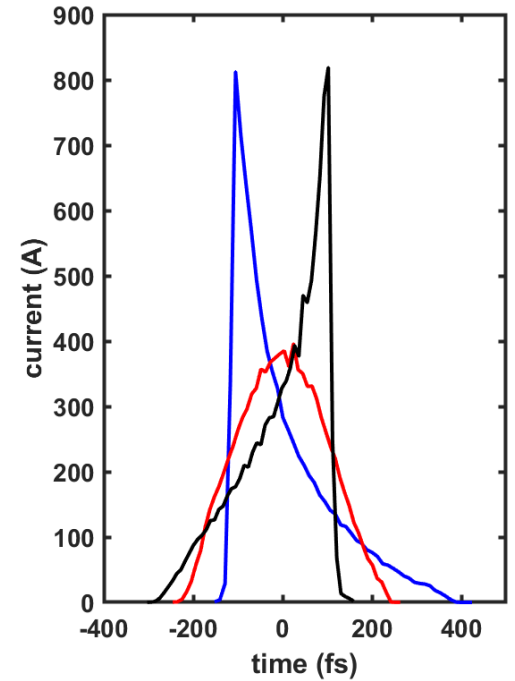
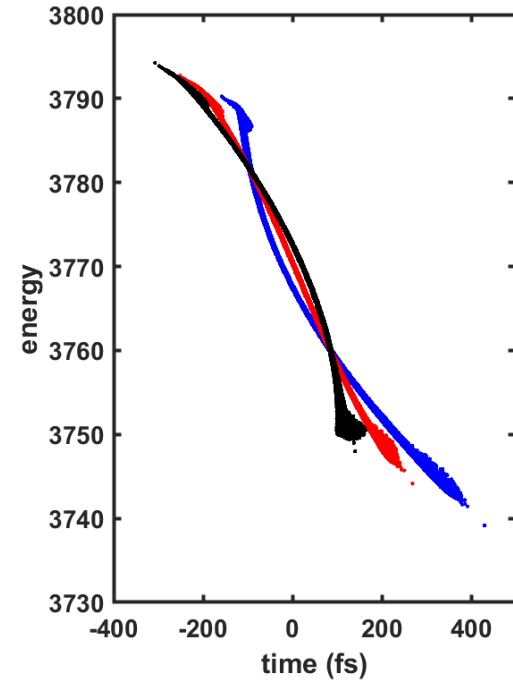
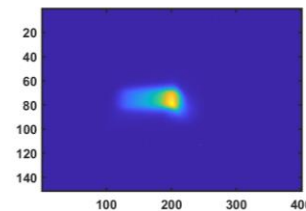
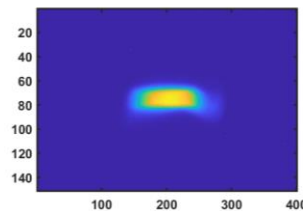
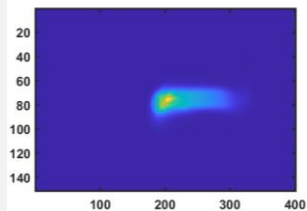
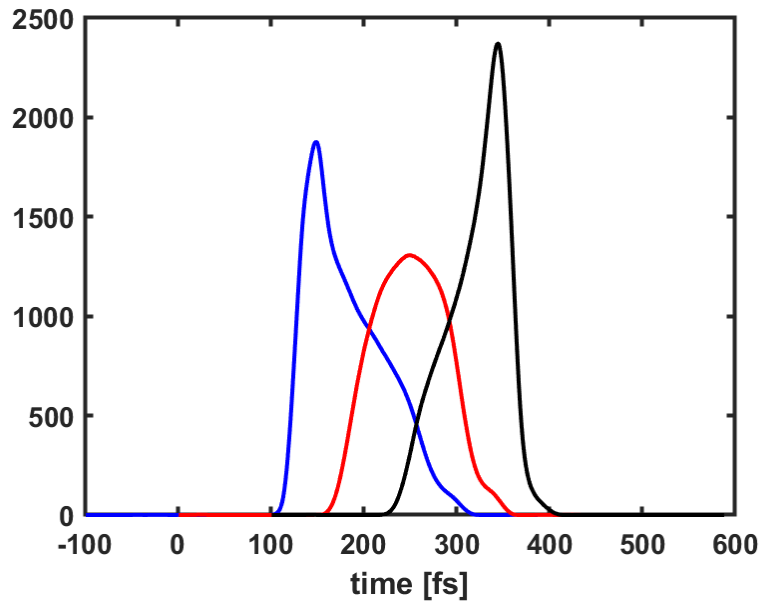
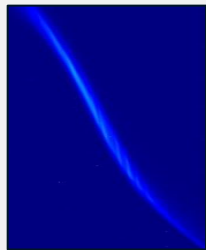
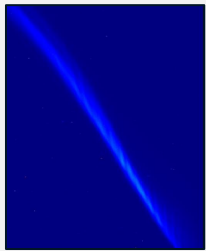
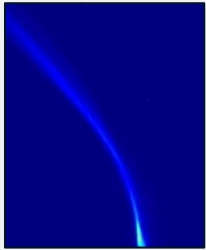


Corresponding elegant simulation



T566 scan, changing the sextupoles in BC1

Longitudinal phase space (TDC + dipole)

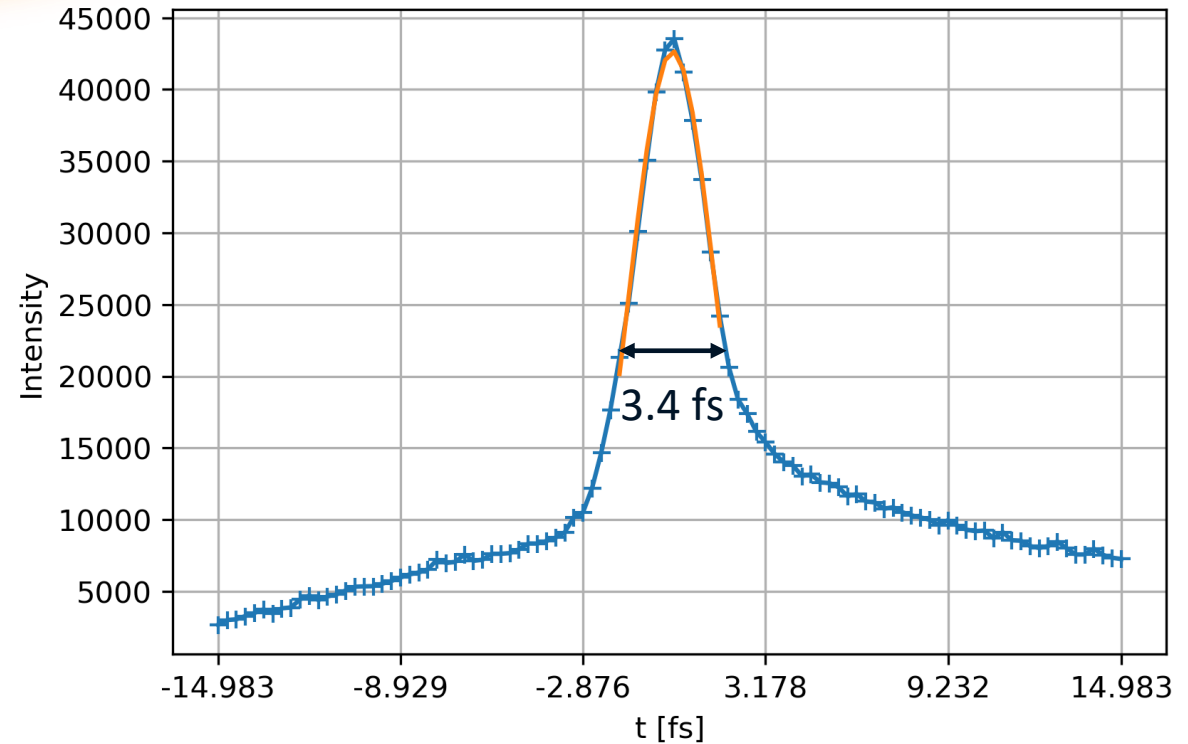
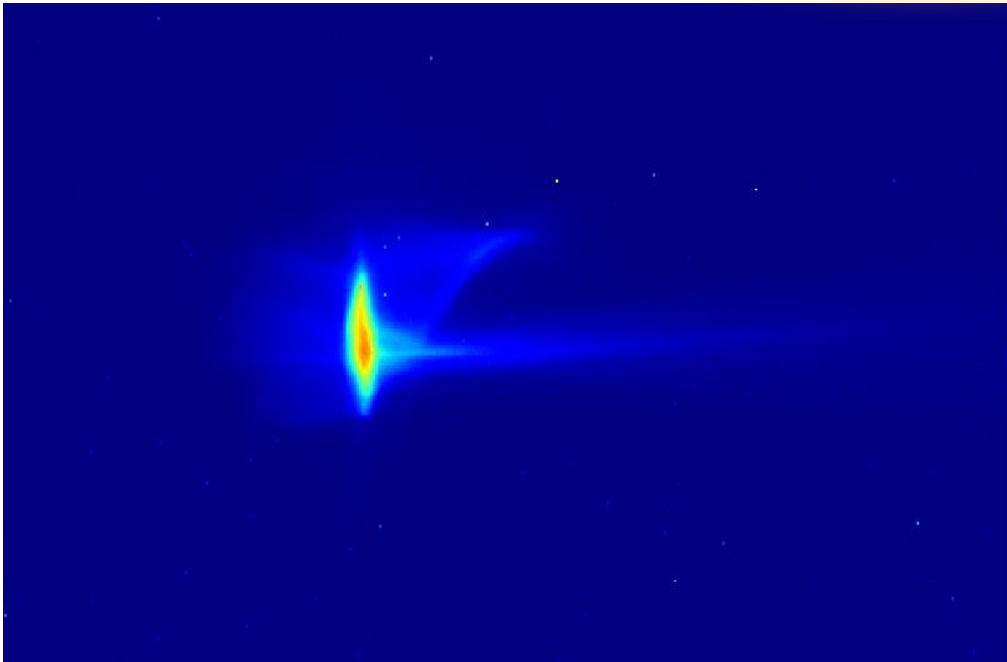


- Under linearised
- Completely linearised
- Over linearised

Shortest bunch measured

3.4 fs fwhm

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



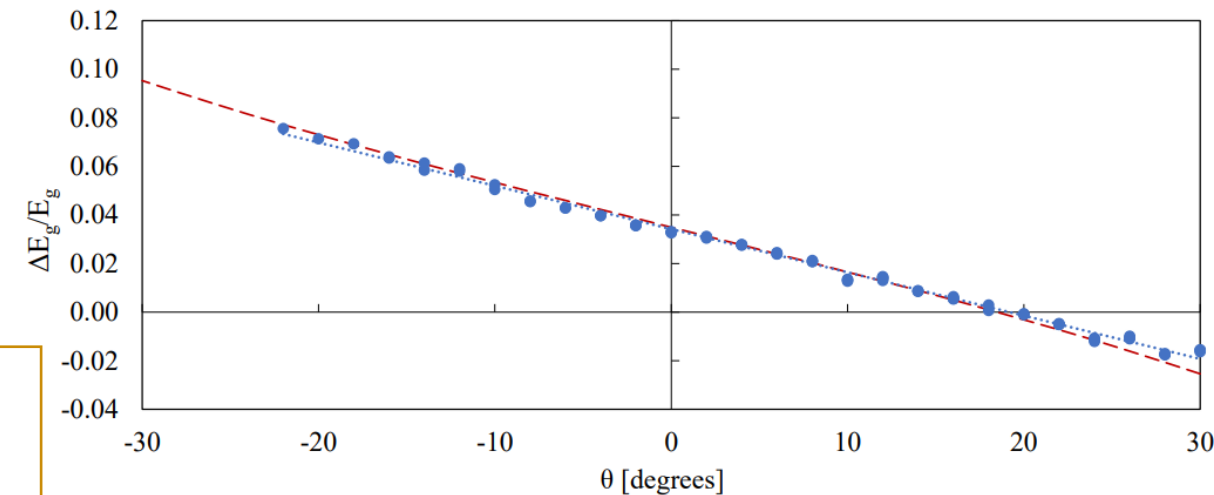
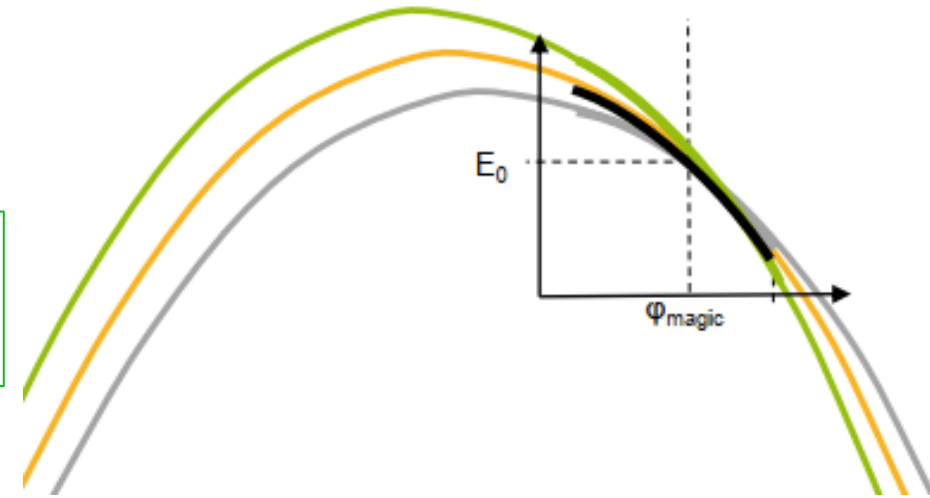
Magic angle

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.

- Talk by Erik last FEL
- 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 at MAX IV in Erik's talk tomorrow.

Low-jitter conversion from optical references to electrical radio frequency signals THAC04



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
- 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.

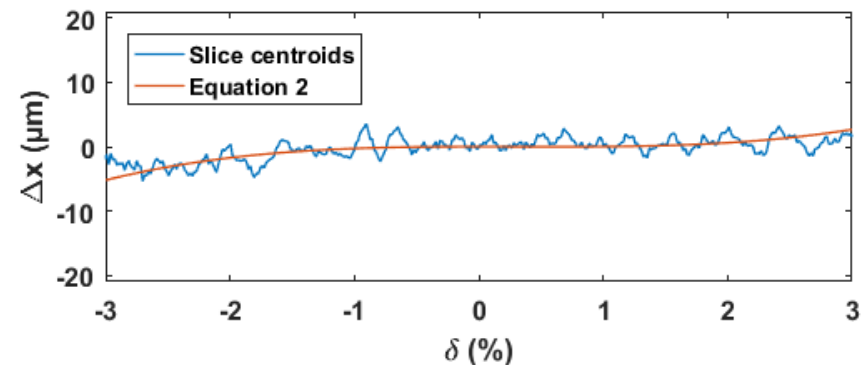
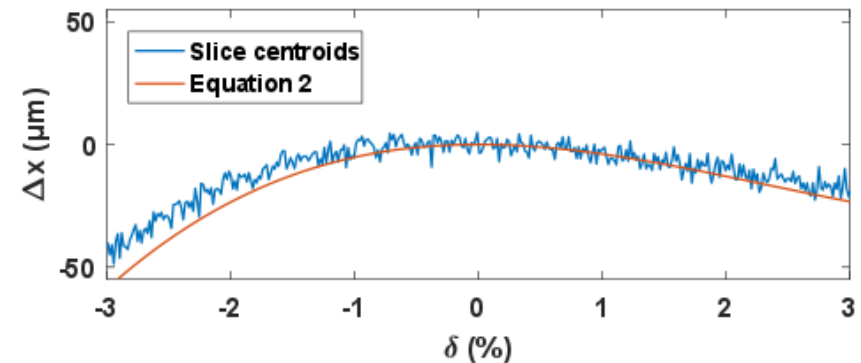
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Mitigation

- 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.

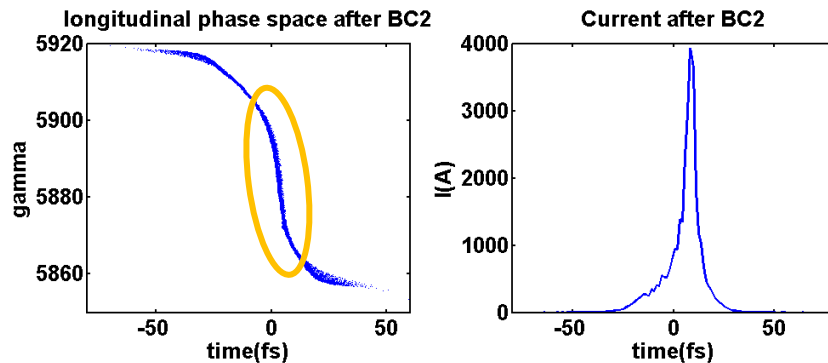


Drawbacks of arc compression

- 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.

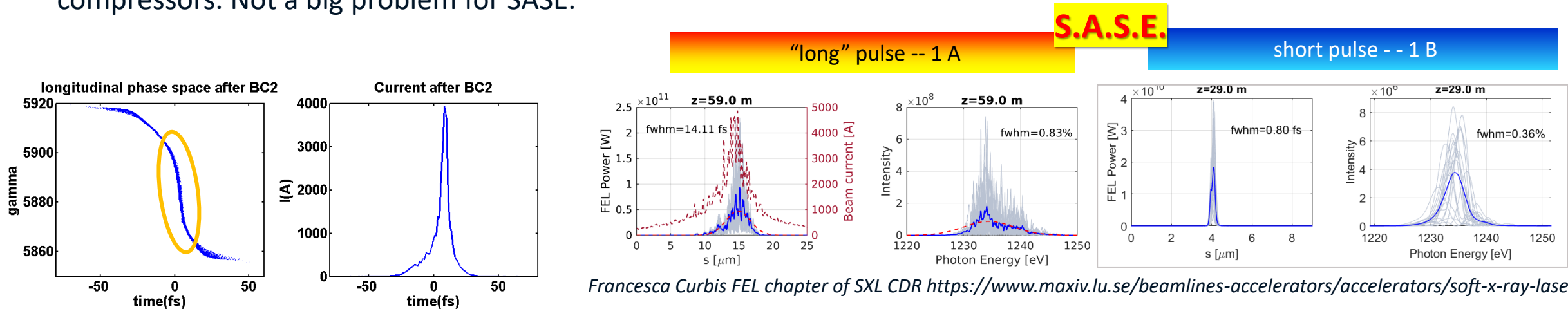
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- Residual energy chirp – the wakes in the linac work towards larger chirp, not to reduce it as for chicane compressors.



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- 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.



Drawbacks of arc compression

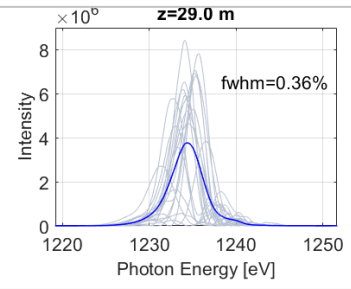
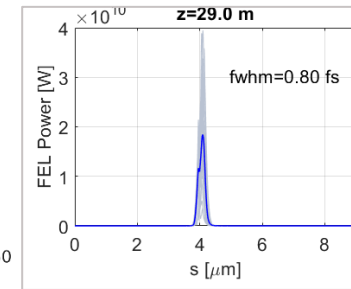
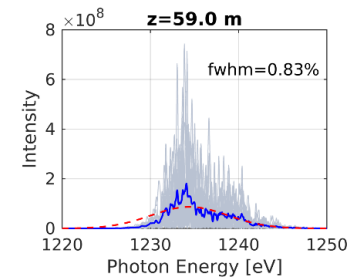
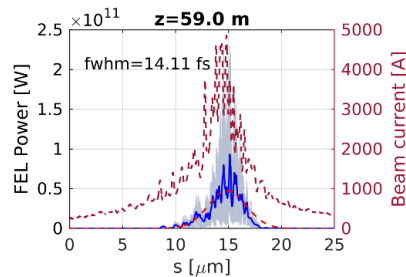
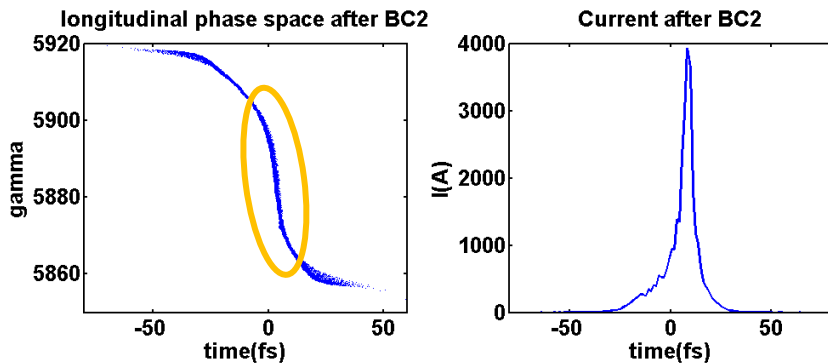
- Chromatic effects – in the current MAX IV compressors there is only one family of sextupoles – second order momentum compaction closure and linearization are not independent.
- Longer and cause a translation of the beamline – BC1 moves the beam 2 meters sideways early in the tunnel, which then just 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.

S.A.S.E.

“long” pulse -- 1 A

short pulse -- 1 B



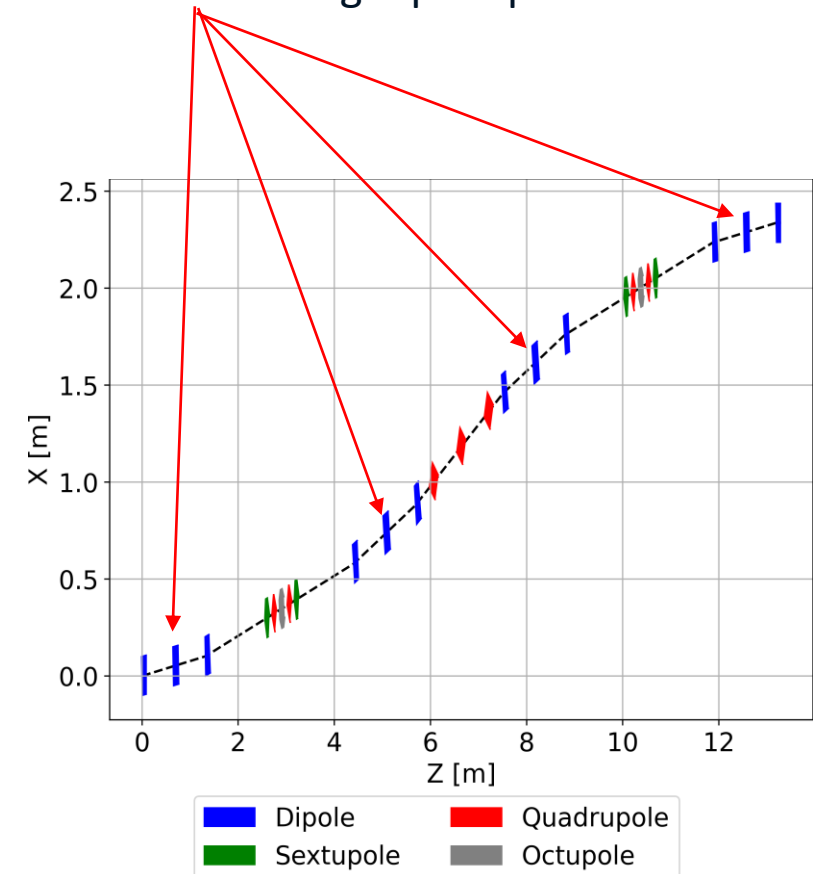
Francesca Curbis FEL chapter of SXL CDR <https://www.maxiv.lu.se/beamlines-accelerators/accelerators/soft-x-ray-laser>

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

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).)

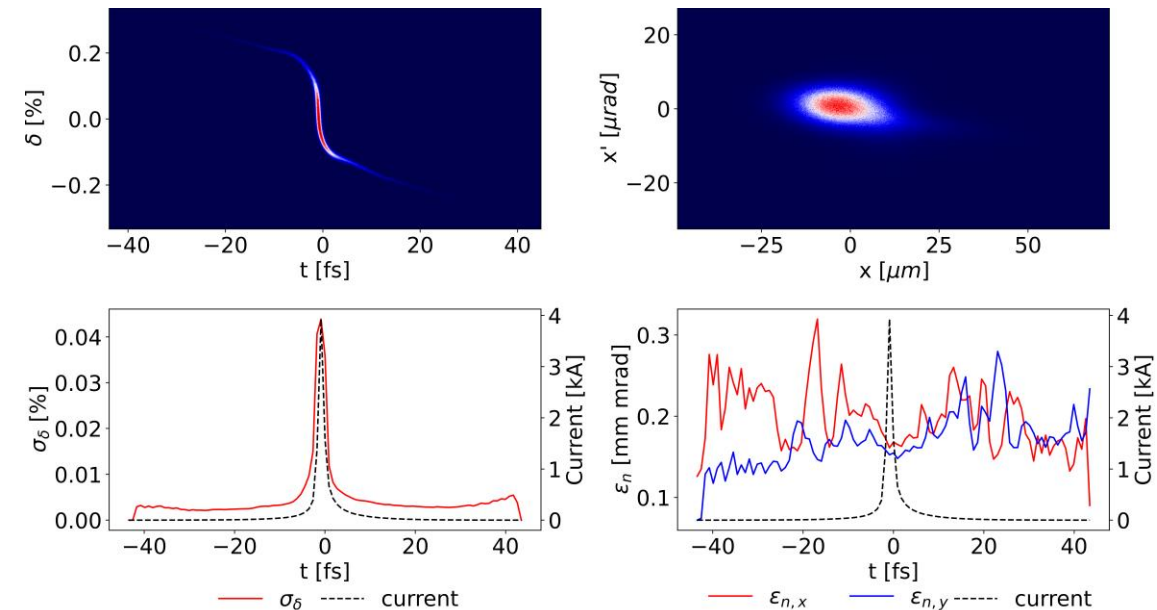
Additional dipoles placed between existing dipole pair.



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

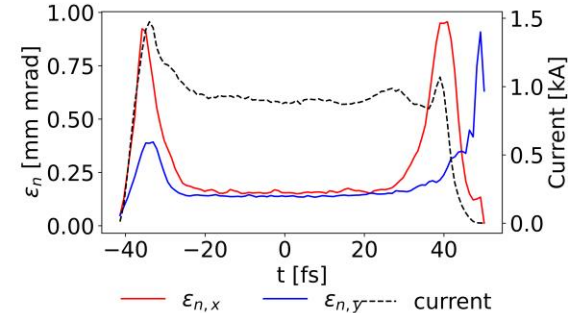
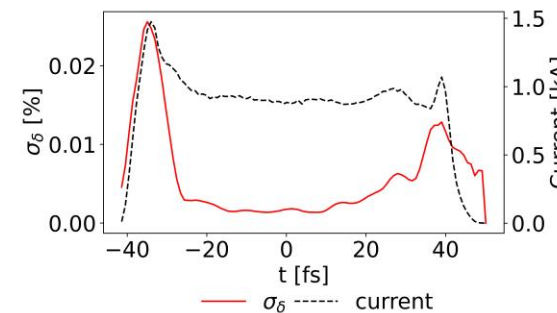
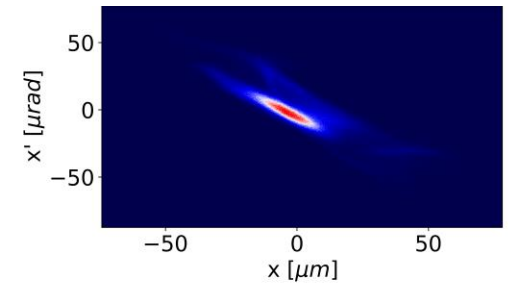
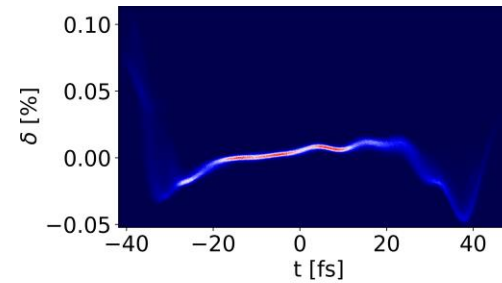


Adam Dixon, et al. *Reduction of arrival time jitter or energy spread with arclike variable bunch compressors*
To be published

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).*)

- 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 $R_{56}=0$ and even $R_{56}<0$ mimic chicane compression to get de-chirping in the main linac – reduce the energy chirp.



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

Arc vs Chicane Bunch Compression

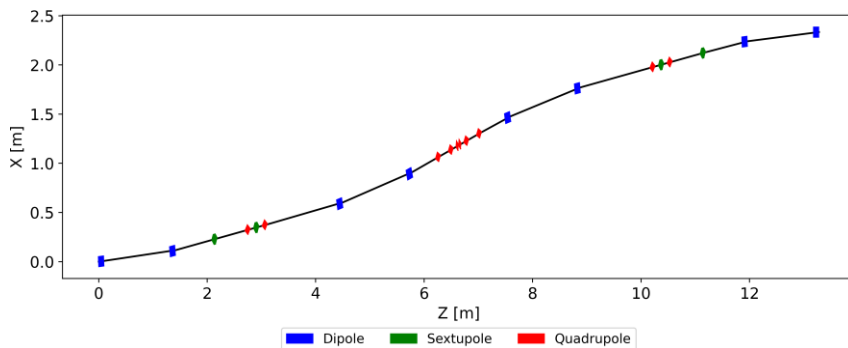
Olivia Karlberg started a study focusing on compression jitter.

(Karlberg, O., Curbis, F., Thorin, S., & Werin, S. *The MAX IV linac as X-ray FEL injector: Comparison of two compression schemes. FEL13*)

Adam Dixon, Peter Williams et.al has taken the concept further, now focusing on compression choices for the UKXFEL...

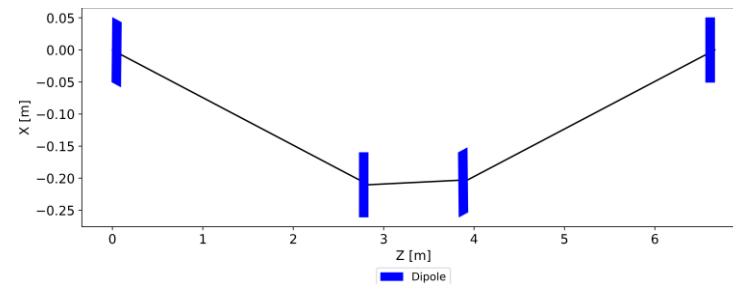
Arc Compression

- $0 < R56$
- $0 < T566$. Self-linearising.
- Coherent synchrotron radiation induced emittance growth mitigation by π -phase advance between achromats.



4 dipole chicane compression

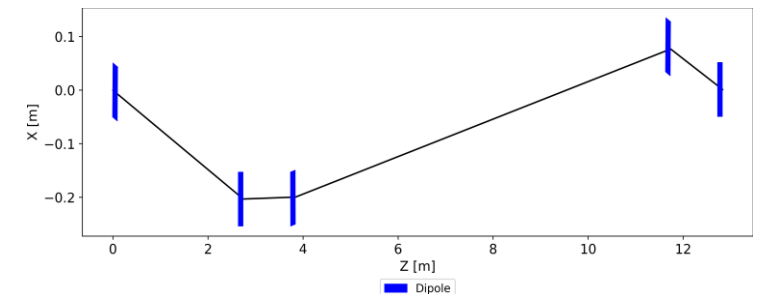
- $R56 < 0$
- $0 < T566$. Requires harmonic linearisation.



5-bend chicane / Asymmetric S-chicane

(Khan and Raubenheimer. *Phys rev. AB 25, 090701* (2022)) /Fancong Zeng, Yi Jiao, Weihang Liu, and Cheng-Ying Tsai, e-Print: 2403.06101 [physics.acc-ph]

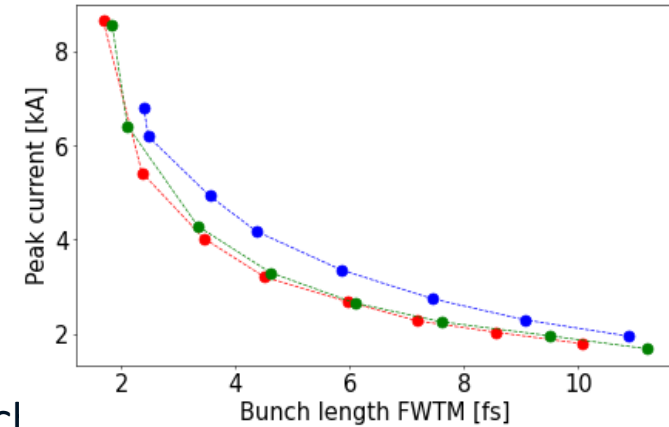
- $R56 < 0$
- $0 < T566$. Requires harmonic linearisation.
- Coherent synchrotron radiation induced emittance growth mitigation from geometry of chicane.



Arc vs Chicane Bunch Compression

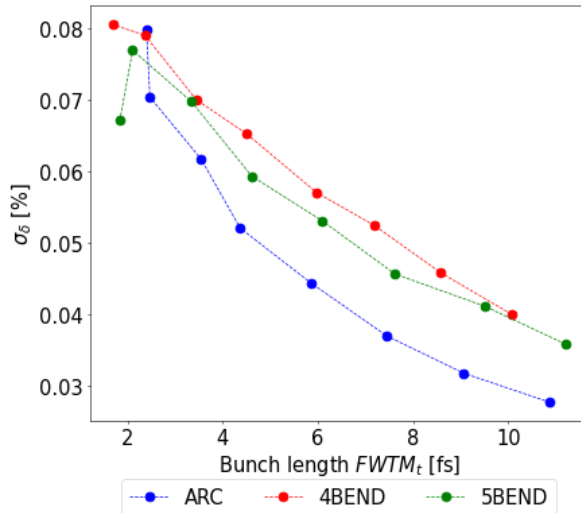
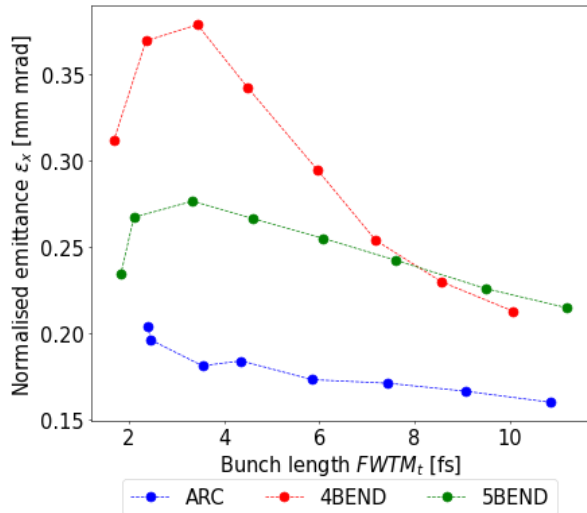
- Peak current is measured against bunch length – arc has higher peak current for a given bunch length except for minimised bunch length.
- Emittance and energy spread of peak current slice is measured.
- SASE FEL saturation power and gain length calculated for peak current slice using analytical approximation. (*M. Xie (LBL, Berkeley) Conf.Proc.C 950501 (1996), 183-185*)

Peak Current

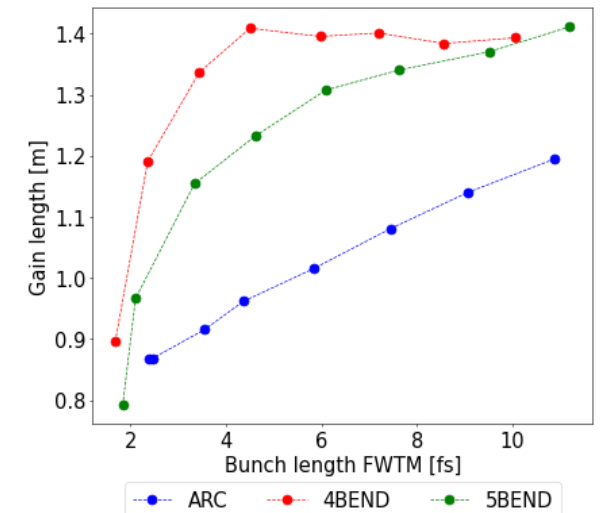
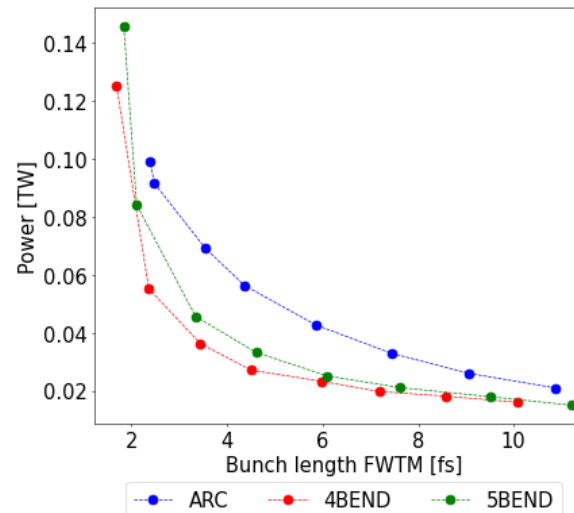


Main Linac Phase Scan – 10 pC Bunch

Peak Current Slice



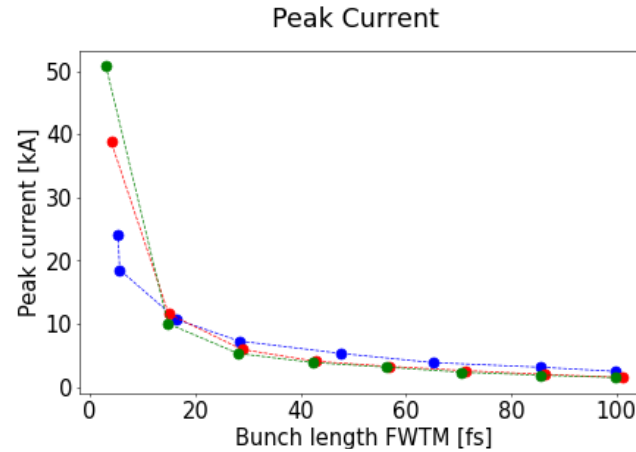
Bunch length - Ming Xie



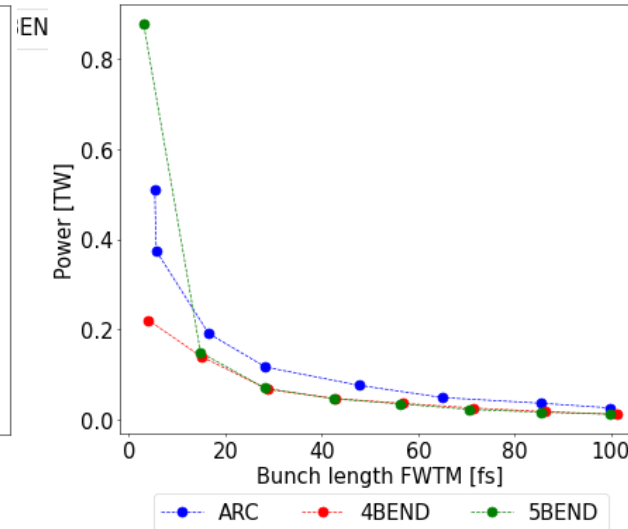
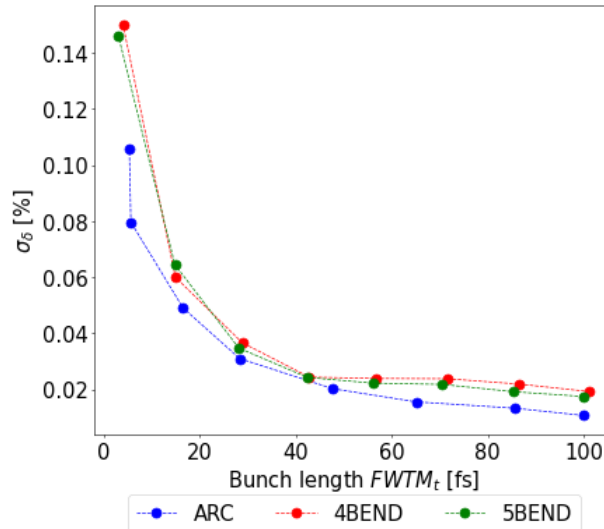
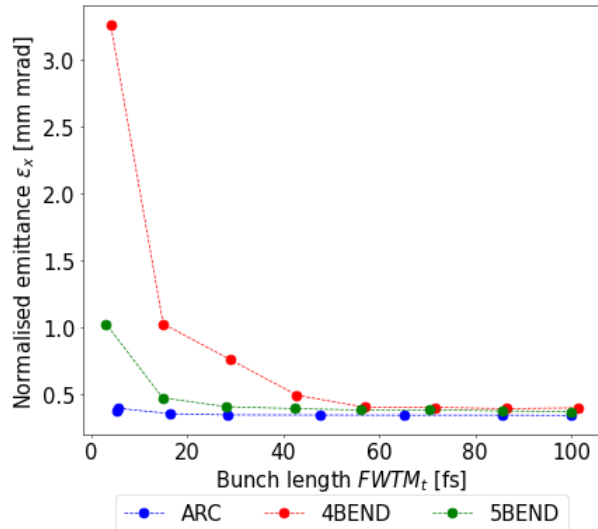
Arc vs Chicane BC

Main Linac Phase Scan
– 100 pC Bunch

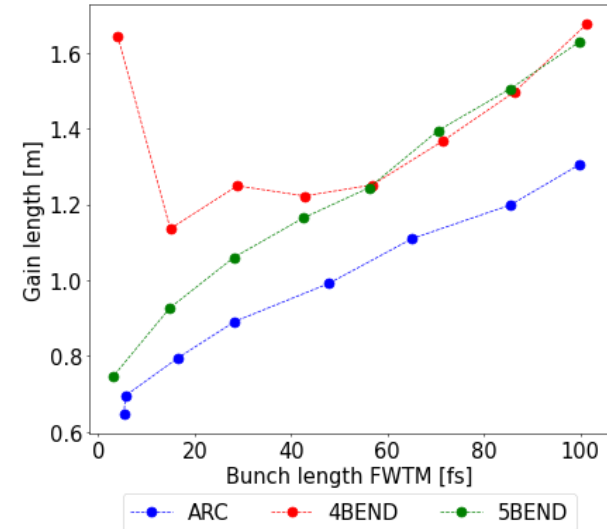
- Peak current higher for arc until we to very short bunches
- Slice emittance, stays lower for arc and asymmetric/5-bend chicane
- Slice energy spread lower for the arc
- SASE power and gain length calculated with the analytical approximation by Ming Xie – the arc is more efficient until very short bunches.



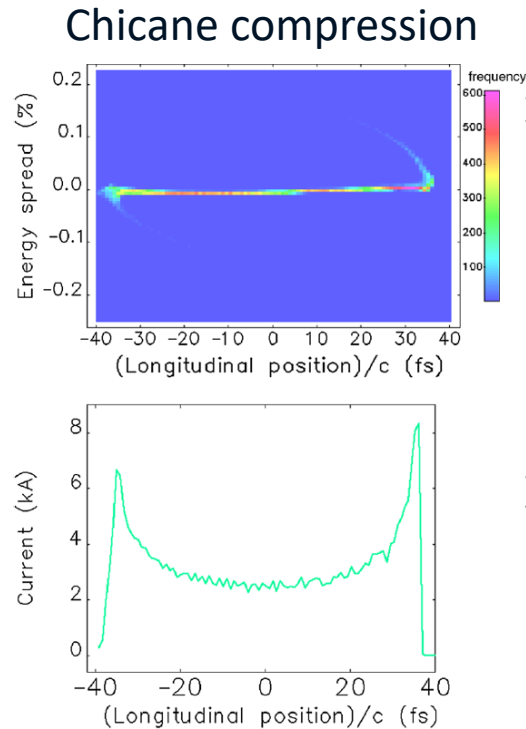
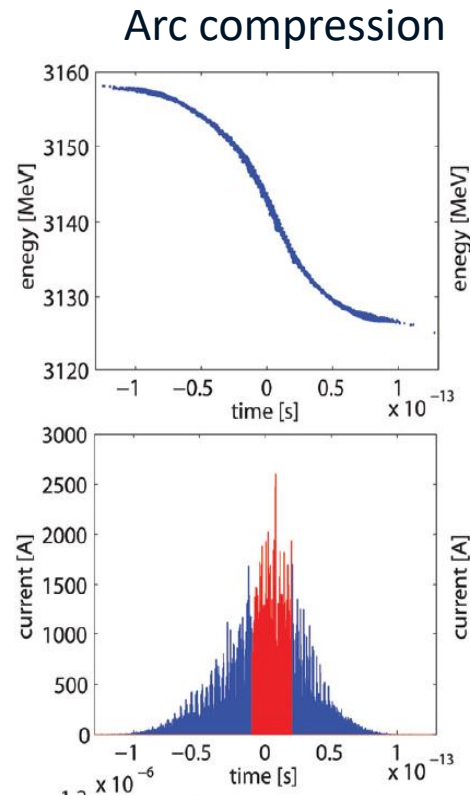
Peak Current Slice



Bunch length - Ming Xie



Arc vs Chicane BC

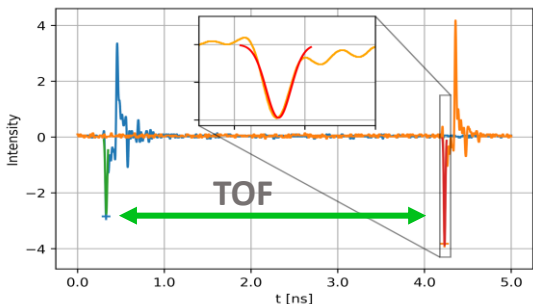
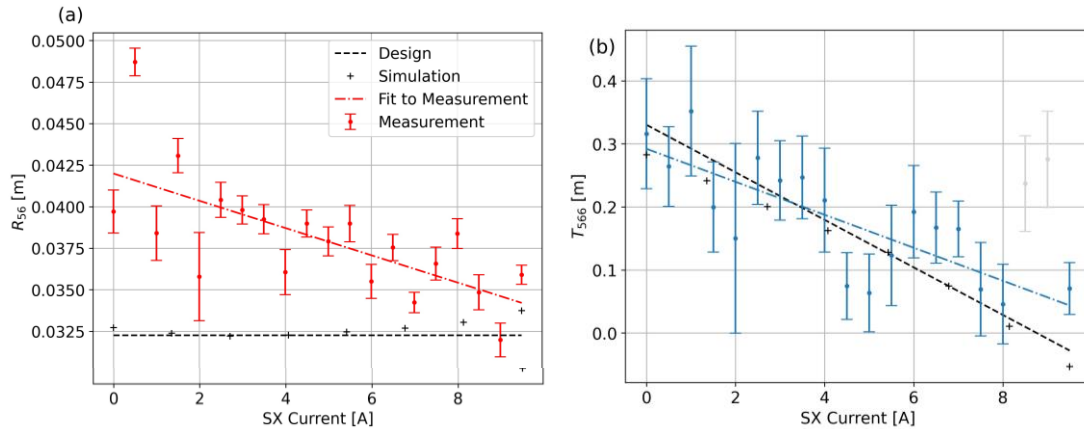


- The comparison is difficult!
- Compression looks very different for arc and chicane like compression.
- Several ways to optimize the bunch for each bunch length and peak current, depending on the compressor setup.
- **One clear conclusion from the comparison – the 4 dipole chicane causes emittance degradation due to the church tower CSR kicking the center of the beam.**

Recent experimental work @ MAX IV BC

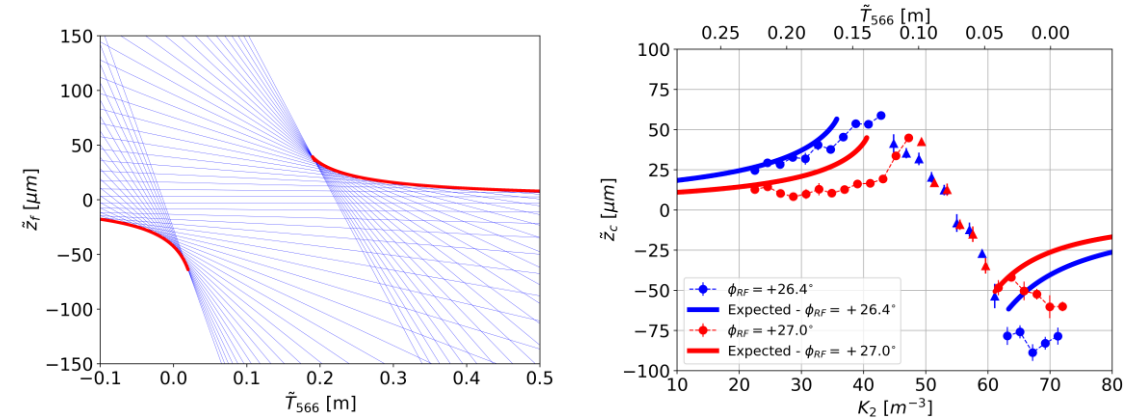
Johan Lundquist Measurement of First and Second Order Longitudinal Dispersion in the MAX IV Bunch Compressor

TUP006



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

Adam Dixon Measurements of Particle Trajectory Caustics in Bunch Compressors TUP090



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.

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.
- The main benefits of arc compression include:
 - energy saving due to not losing 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 dependent 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.
- Simulation show that a 5 dipole/asymmetrical chicane can solve the CSR induced emittance degradation, but it lacks many of the other arc benefits.

Acknowledgement



- Mikael Eriksson, Erik Mansten and the linac team @ MAX IV
- Peter Williams (STFC Daresbury Lab & Cockcroft Inst)
- Adam Dixon, Andy Wolski (The University of Liverpool)
- Francesca Curbis, Johan Lundquist, Sverker Werin, Jonas Björklund Svensson (MAX IV, Lund University)
- Tessa Charles (Australian Synchrotron)
- Gustavo Perez-Segurana (Cern)

