First Experimental Measurements of the Caustic Nature of Trajectories in Bunch Compressors

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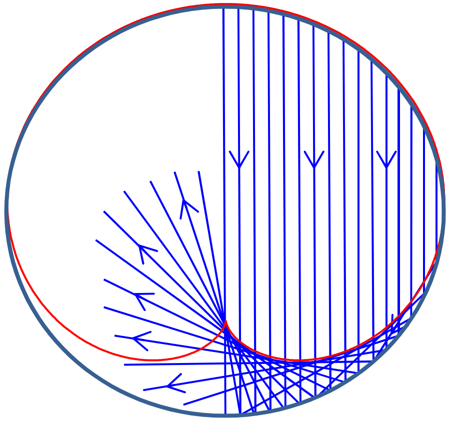
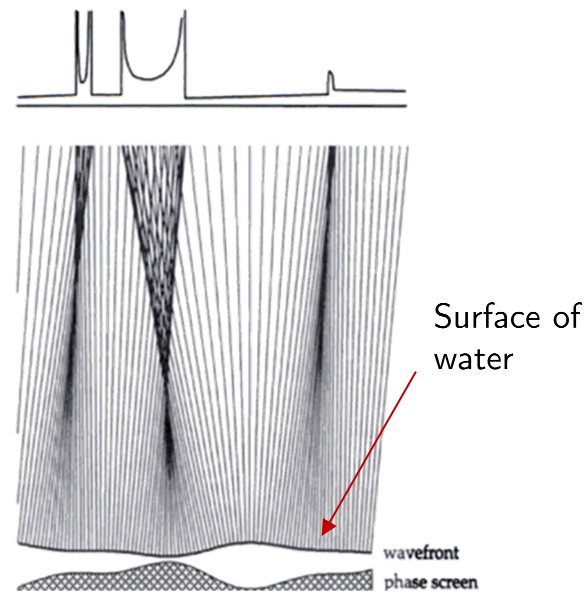
4. MAX IV Laboratory, Lund, Sweden

The envelope of trajectories forms the caustics lines.

Caustics lines are an envelope of trajectories, or the projection of that envelope on another surface.



J.F. Nye "Natural Focusing and Fine Structure of Light: Caustics and Wave Dislocations", (Taylor & Francis, Philadelphia, 1999).

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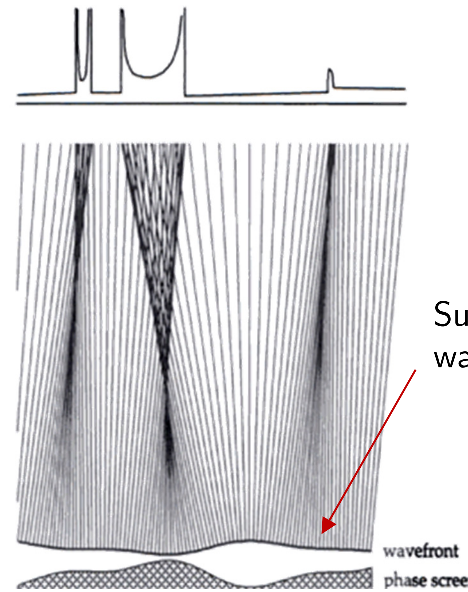


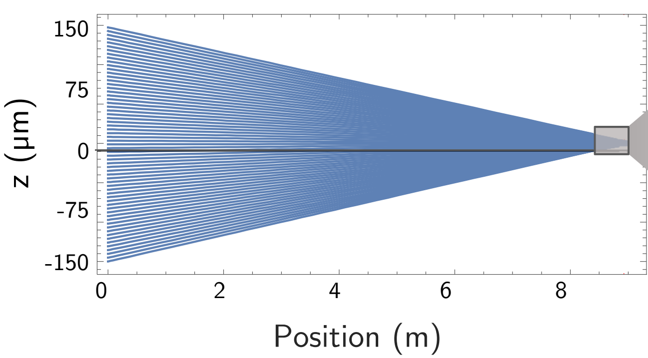
J.F. Nye "Natural Focusing and Fine Structure of Light: Caustics and Wave Dislocations", (Taylor & Francis, Philadelphia, 1999).

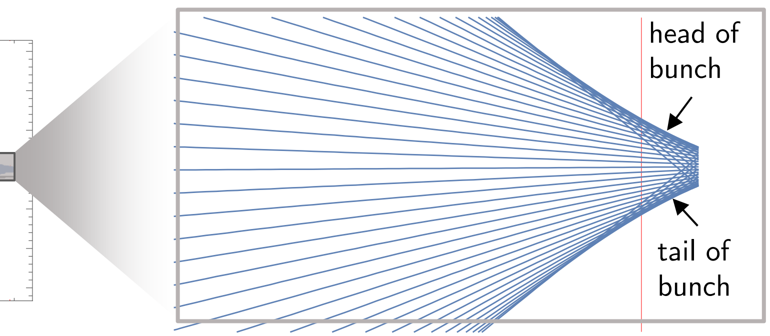
Outline

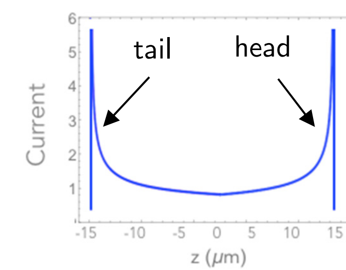
1. Introduction of caustics
2. Example of the usefulness of caustics
3. MAX IV experimental set up & results

Caustics in accelerator physics

Electron trajectories in a bunch compressor:

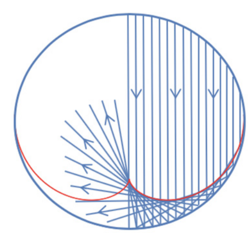


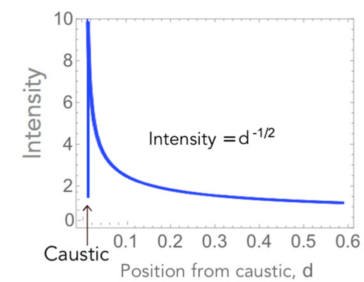




Where there are caustics, there will be current spikes.

Optical caustics:





Caustics are singularities in the density of families of trajectories.

Caustics fall into catastrophe theory

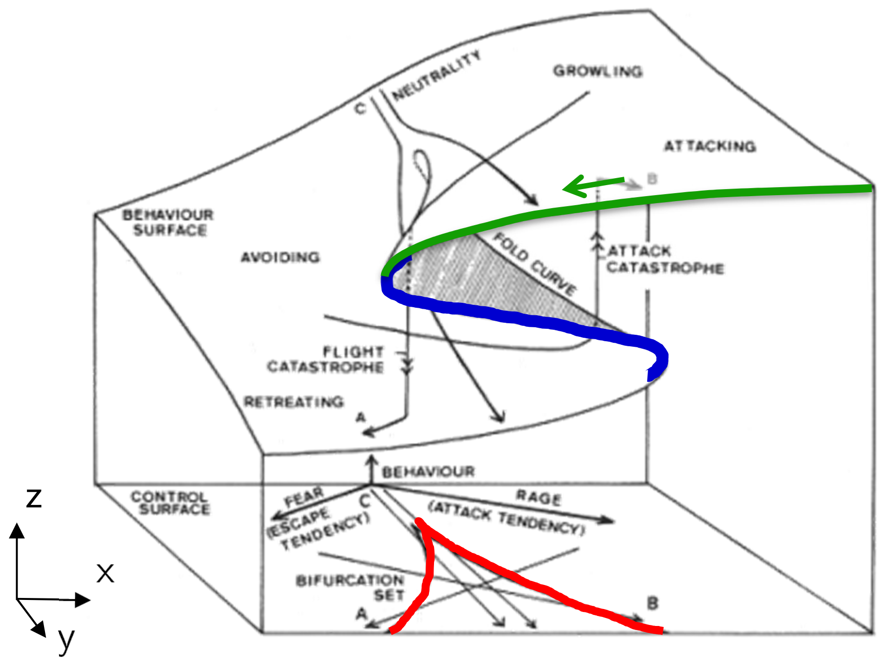
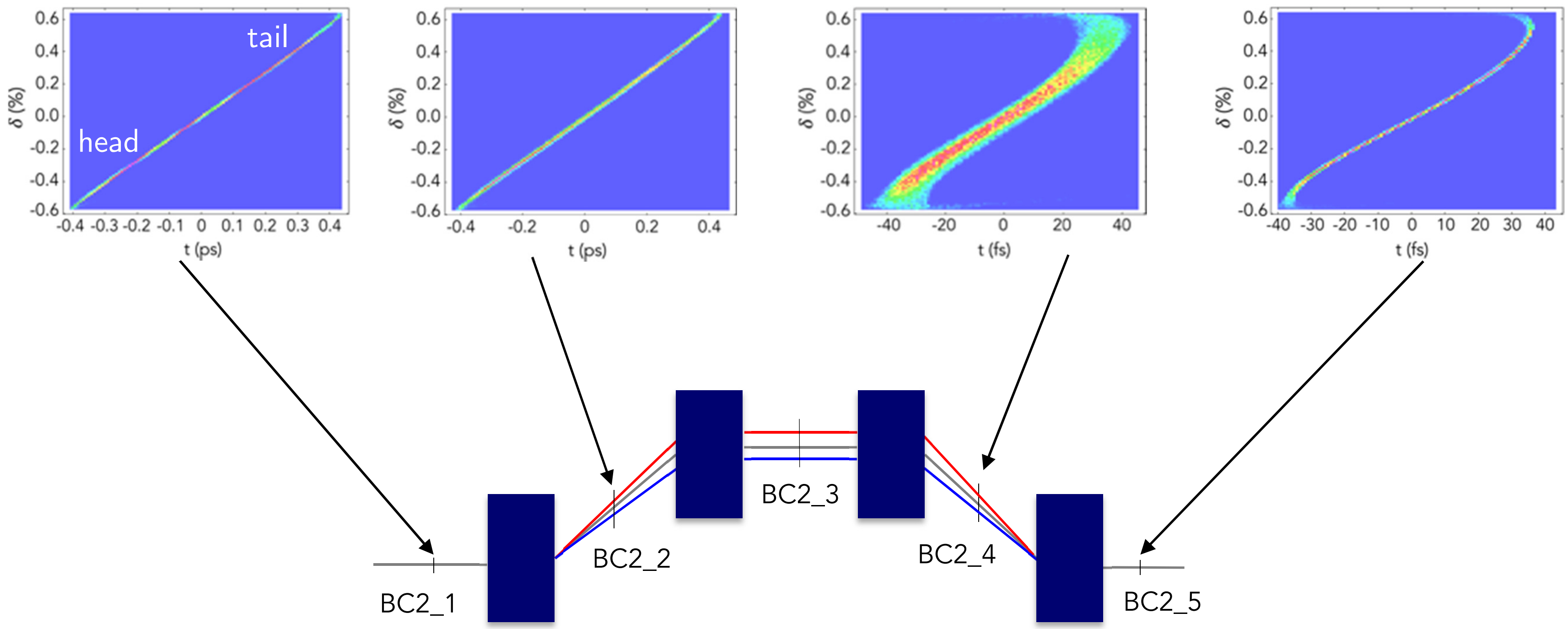
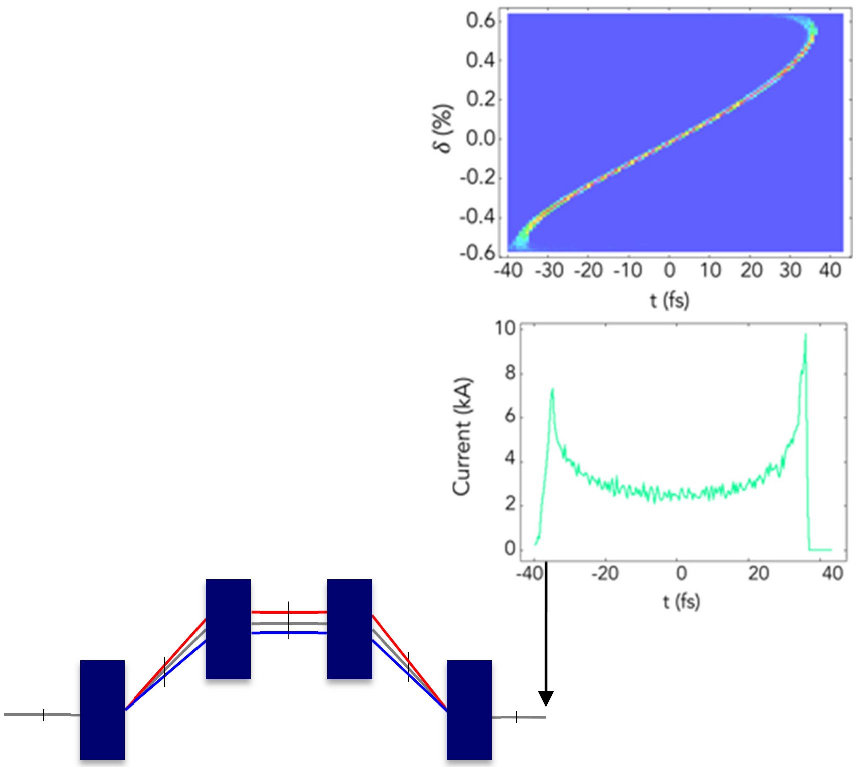


Figure: EC Zeeman (1976) Catastrophe Theory in Scientific American.

Phase space evolution through a bunch compression



Phase space evolution through a bunch compression



Energy spread induced by CSR:

λ = linear charge density

$$\frac{dE}{cdt} = \frac{-2e^2}{4\pi\epsilon_0(3R^2)^{1/3}} \int_{\tilde{z}-z_L}^{\tilde{z}} \frac{d\lambda}{dz}\left(\frac{1}{\tilde{z}-z}\right)^{1/3} dz$$

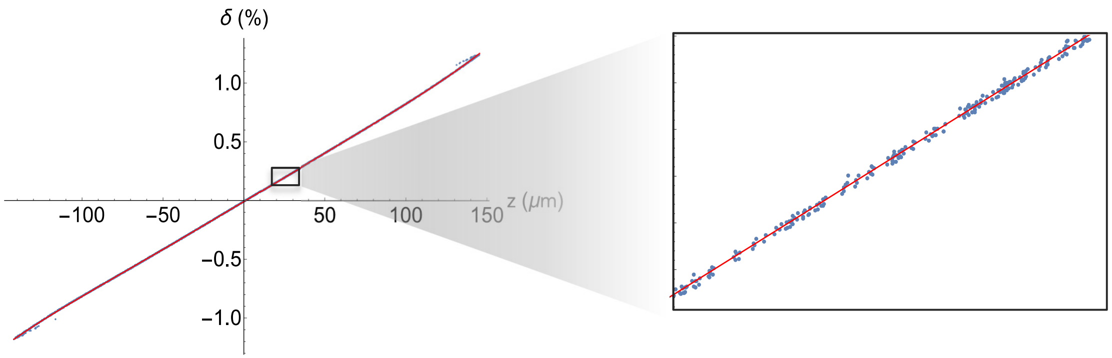
Current spikes are problematic, leading to greater **CSR-induced emittance growth**.

Caustic expression

$$\tilde{z}_c(z_i) = z_i + \frac{\delta(z_i)(-1 + T_{566}(-2+\delta(z_i))\delta'(z_i) + U_{5666}(-3+\delta(z_i)^2)\delta'(z_i))}{\delta'(z_i)}$$

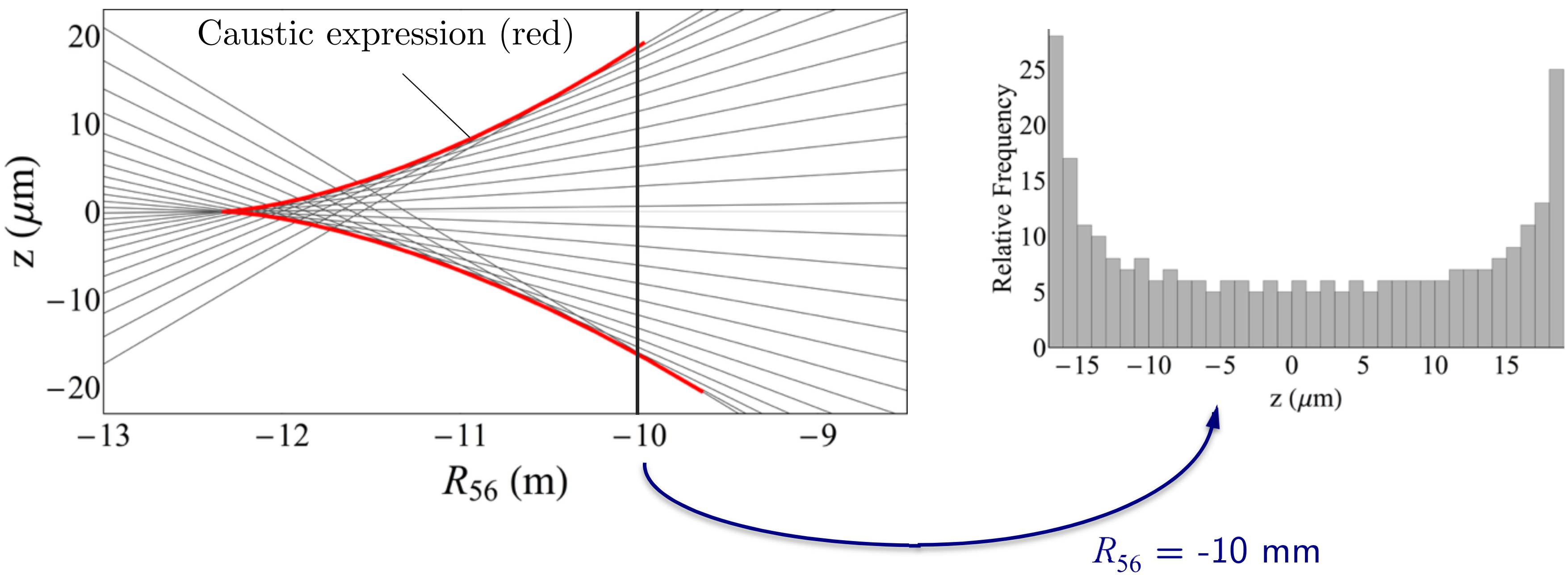
$$\tilde{R}_{56}(z_i) = \frac{-1 - 2T_{566}\delta'(z_i) - 3U_{5666}\delta'(z_i)}{\delta'(z_i)}$$

T. K. Charles *et al.* (2016) Phys. Rev. Accel. Beams, ***19***, 104402



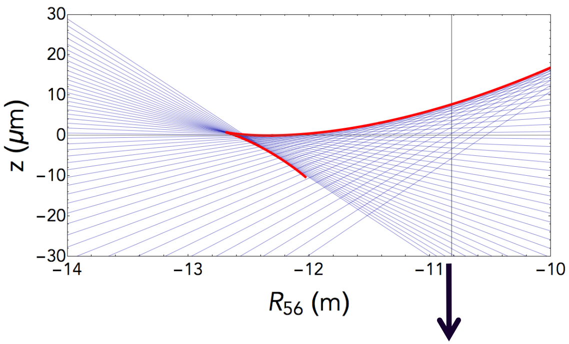
$$\delta(z_i) = h_1 z_i + h_2 z_i^2 + h_3 z_i^3$$

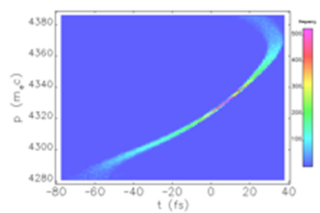
Caustic expression for a chicane



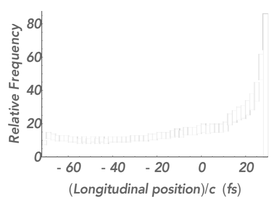
Fold

T_{566} = 18.1 mm, U_{5666} = -24 mm



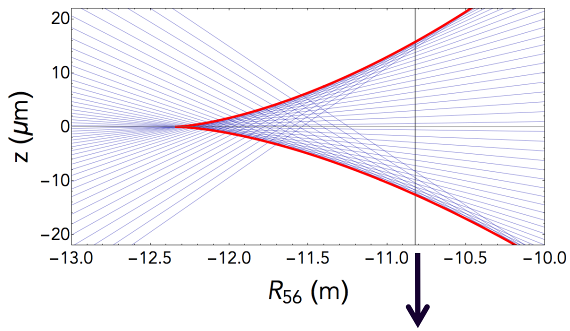


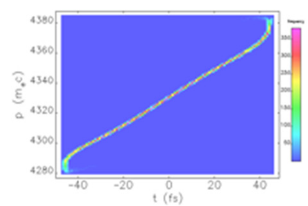
E.g. single spike bunch compression



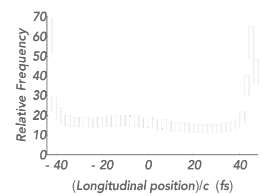
Cusp

T_{566} = 16.4 mm, U_{5666} = -11.4 mm



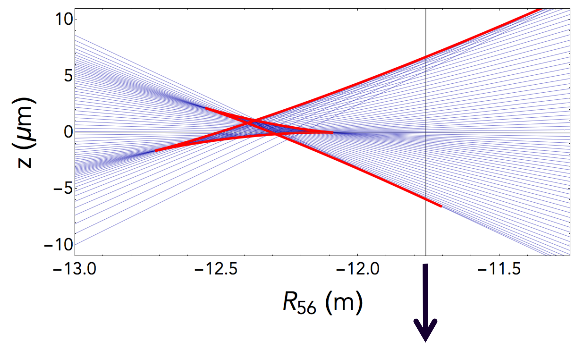


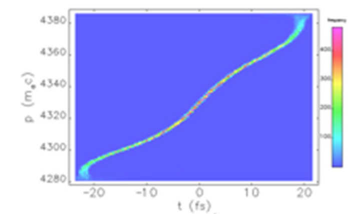
E.g. LCLS
[Y. Ding *et al.* Phys. Rev. AB 19, 100703]



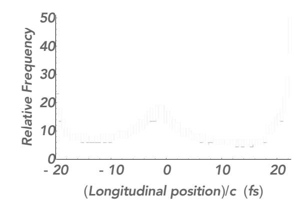
Butterfly

T_{566} =16.1 mm, U_{5666} = 2.6 m





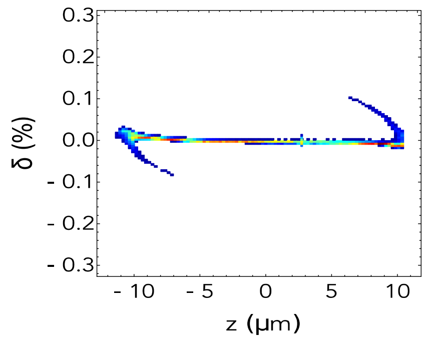
E.g. MAX IV
[S. Thorin *et al.* FEL2010, WEPB34]

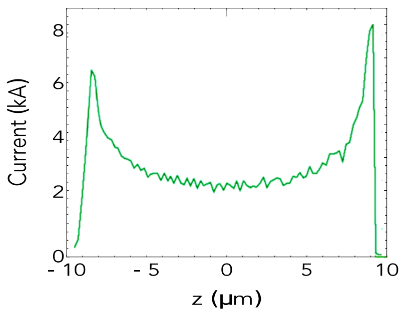


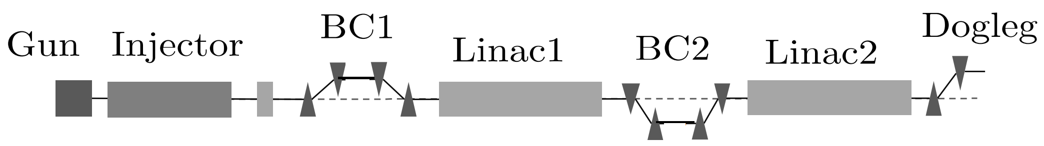
Example of caustics

Current horn suppression

Current horn suppression
An S-band FEL Linac example







Elegant simulations of longitudinal phase space and current profile at the end of Linac2.

Caustic condition

$$R_{56}s\frac{d(\delta(z))}{dz}\bigg|_{z=z_i} + T_{566}s\frac{d}{dz}\left(\delta^2(z)\right)\bigg|_{z=z_i} + U_{5666}s\frac{d}{dz}\left(\delta^3(z)\right)\bigg|_{z=z_i} + s_{BC} = 0.$$

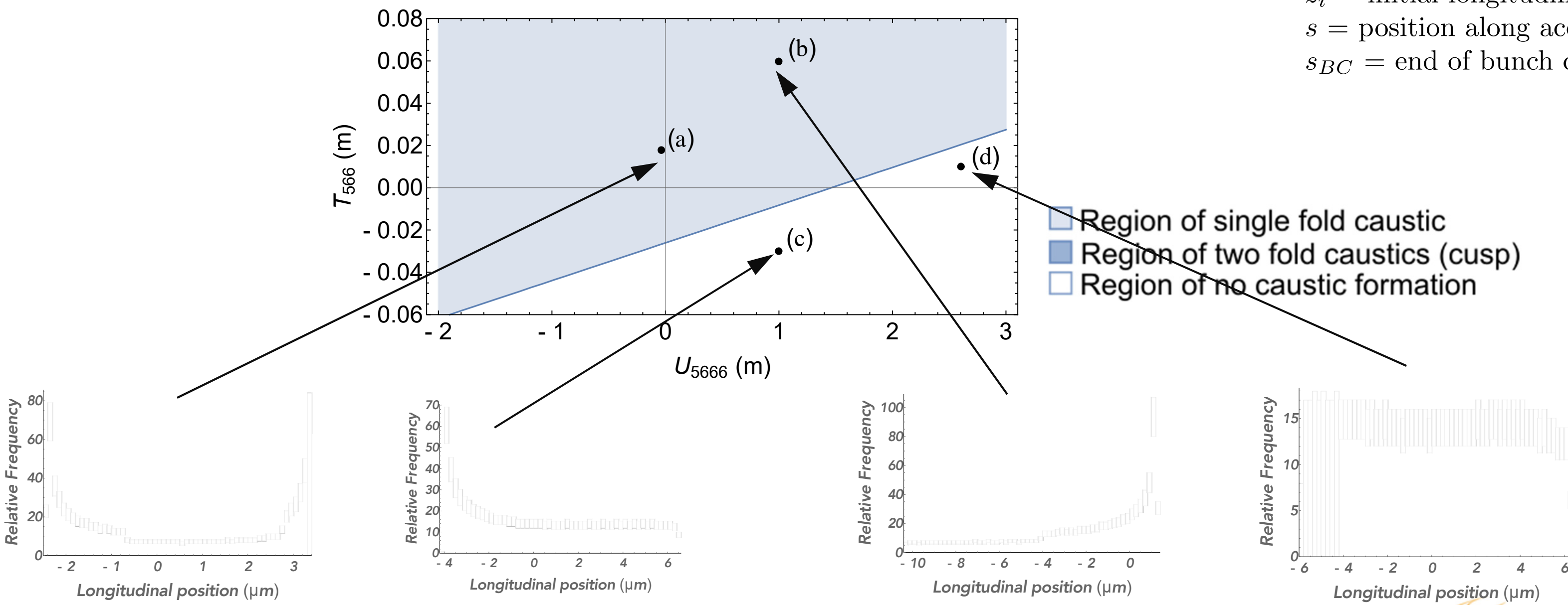
where,

δ = energy spread

z_i = initial longitudinal position

s = position along accelerator

s_{BC} = end of bunch compressor position



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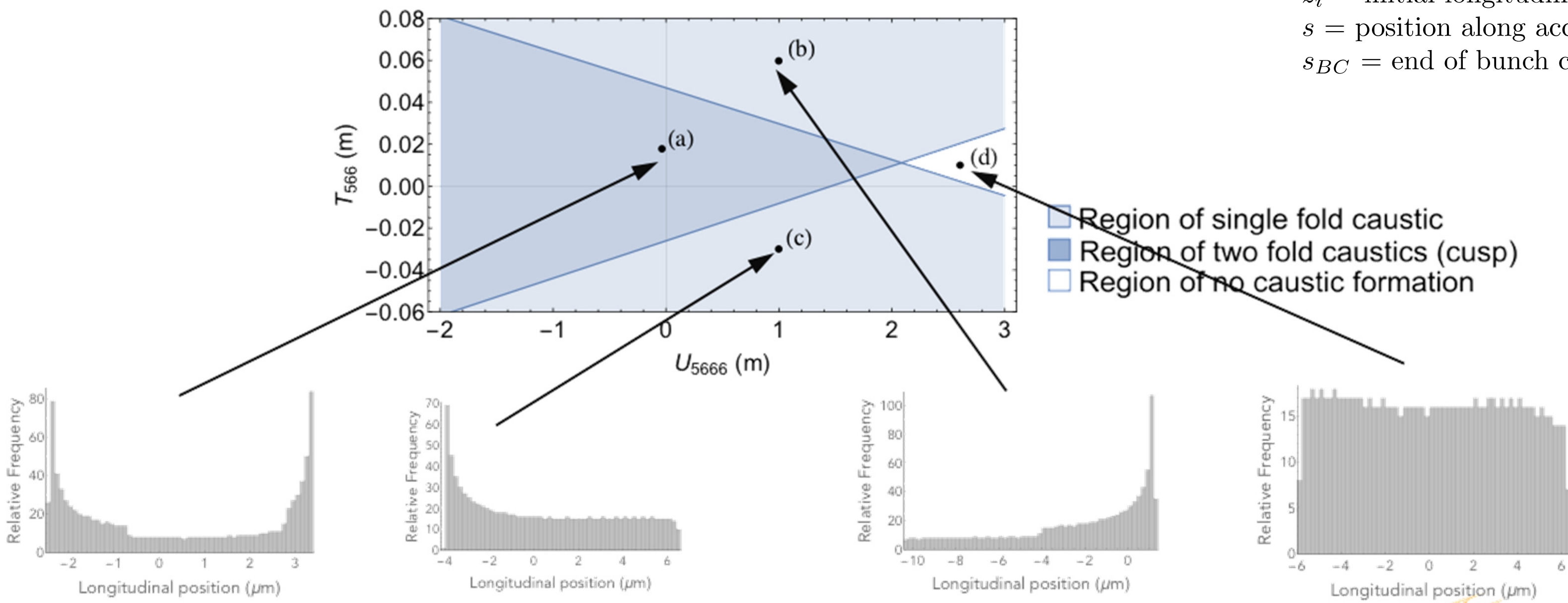
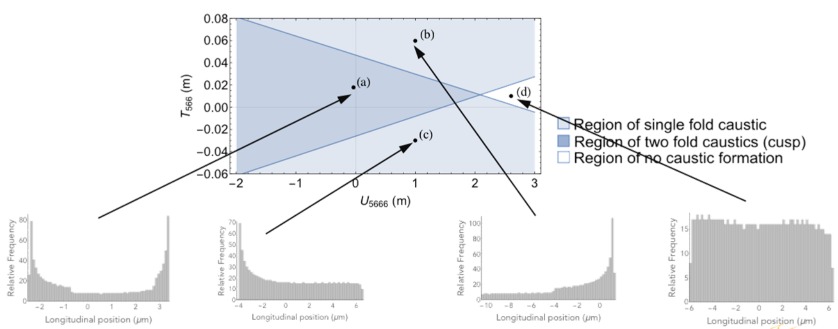


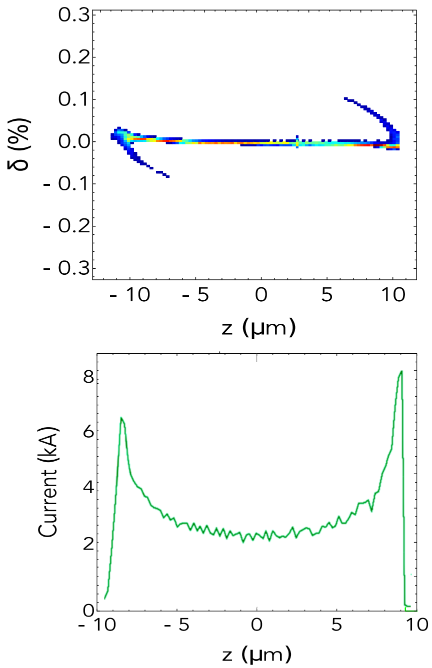
Caustic current horn suppression
S-band FEL linac example

Octupole added to BC1 to vary U5666.



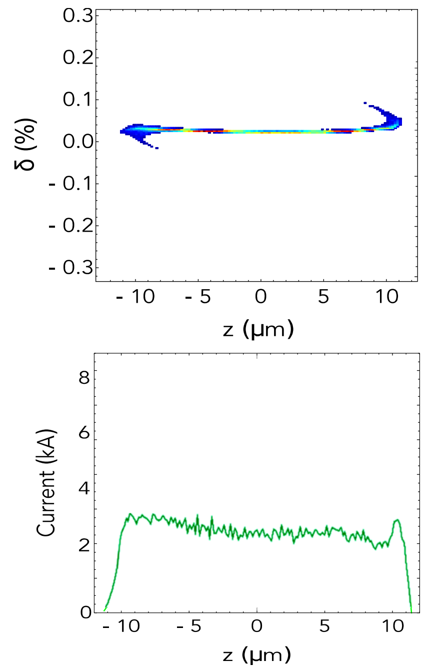
Caustic current horn suppression

Without octupole:



$\epsilon_{nx} = 1.359$ mm mrad

With octupole:



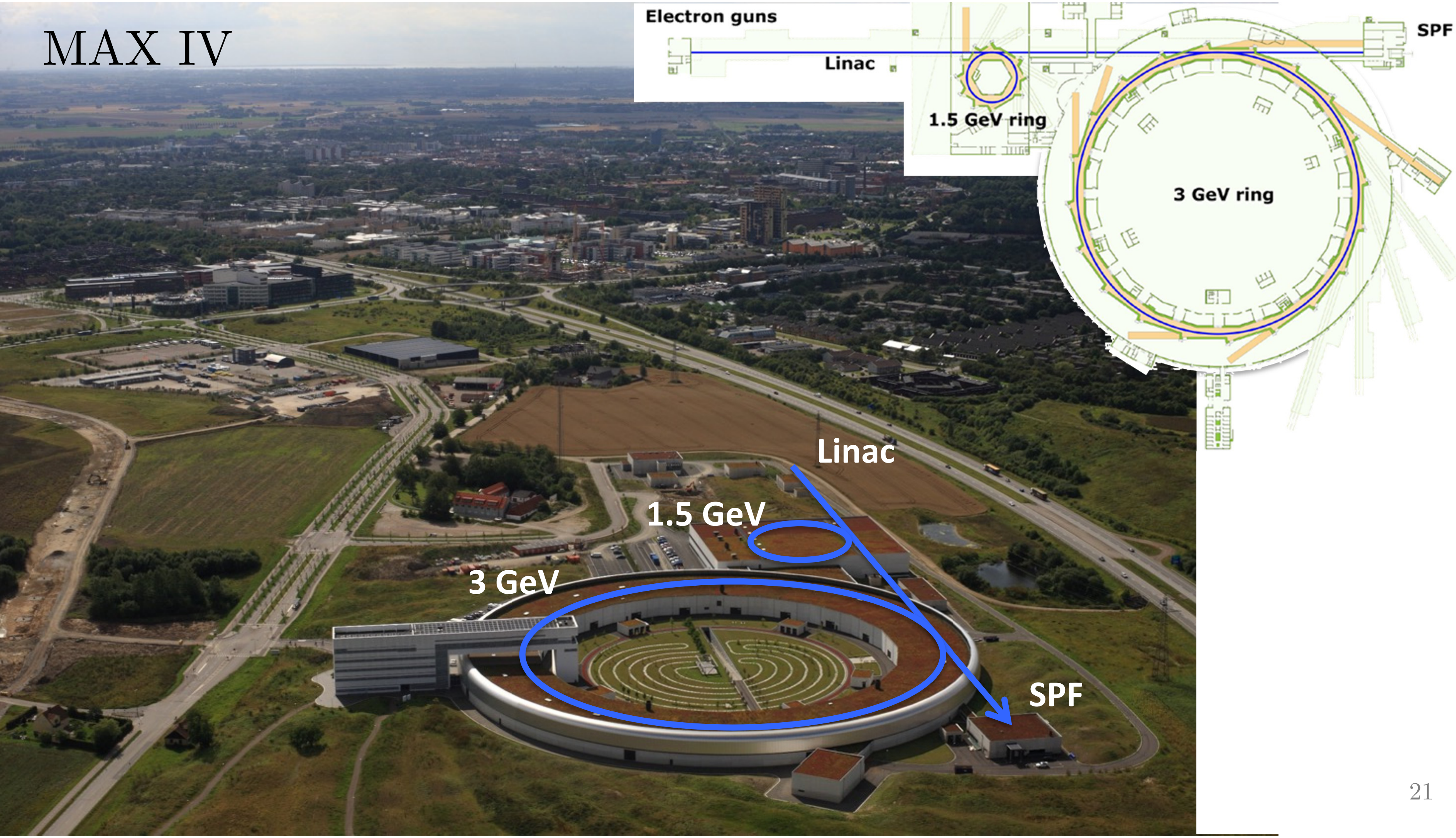
$\epsilon_{nx} = 0.762$ mm mrad

63% reduction in the CSR-induced emittance growth.

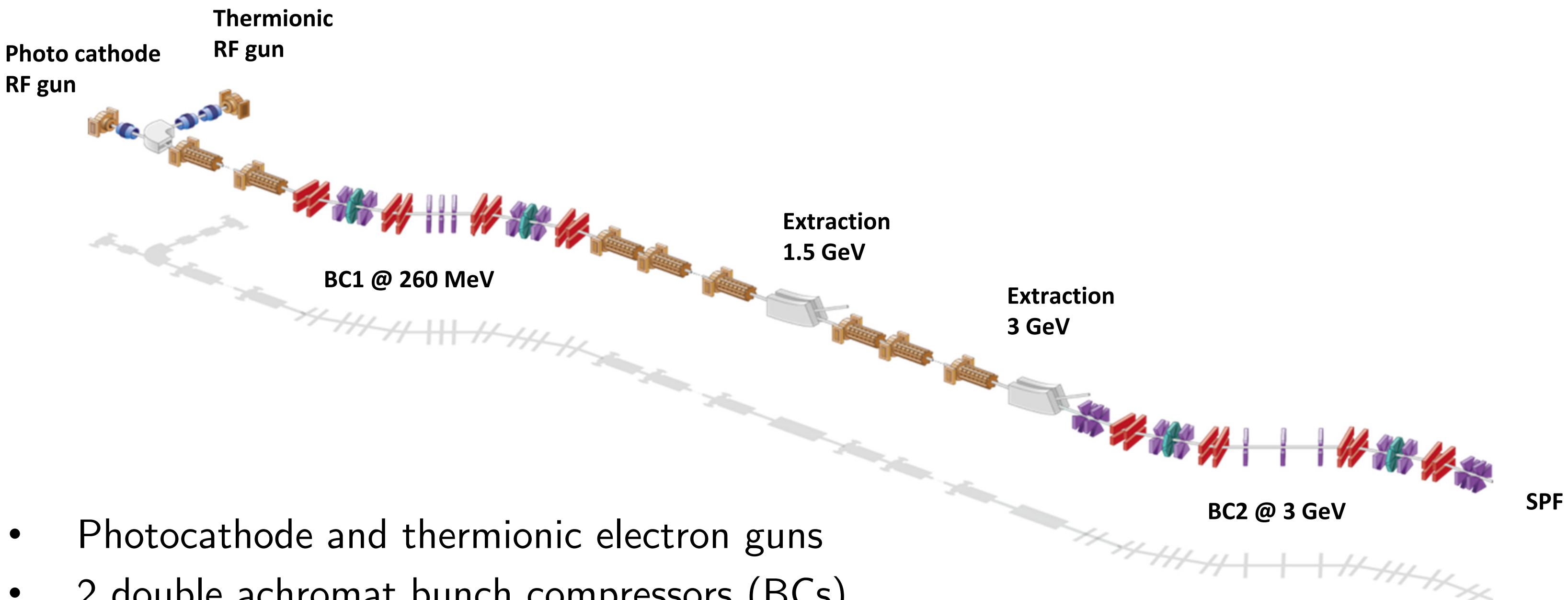
T. K. Charles *et al.* (2017) Phys. Rev. Accel. Beams, ***20***, 030705

Experimental results from MAX IV

MAX IV


Electron guns
Linac
SPF
1.5 GeV ring
3 GeV ring
Linac
1.5 GeV
3 GeV
SPF

MAX IV Linac

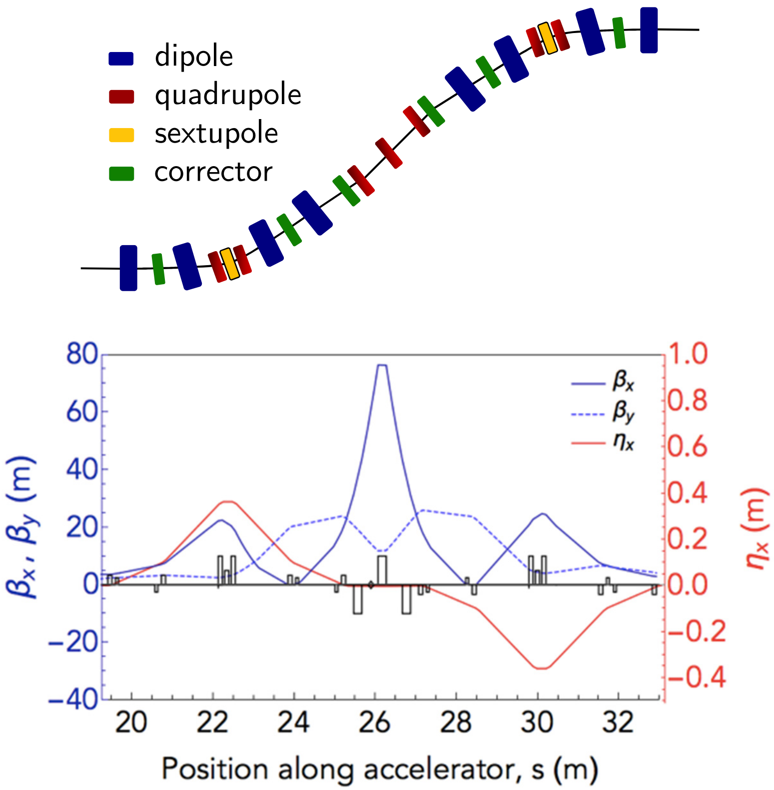


- Photocathode and thermionic electron guns
- 2 double achromat bunch compressors (BCs)
- RF frequency 2.998 GHz

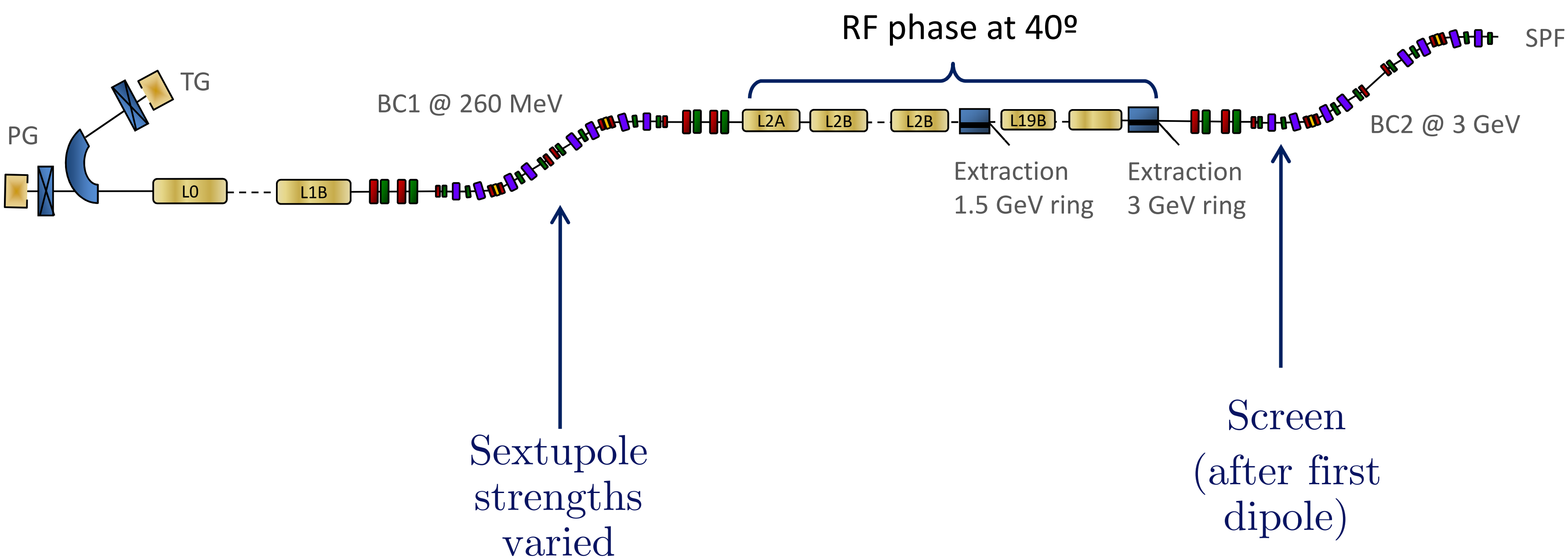
MAX IV Bunch Compressors

Double achromat bunch compressors:

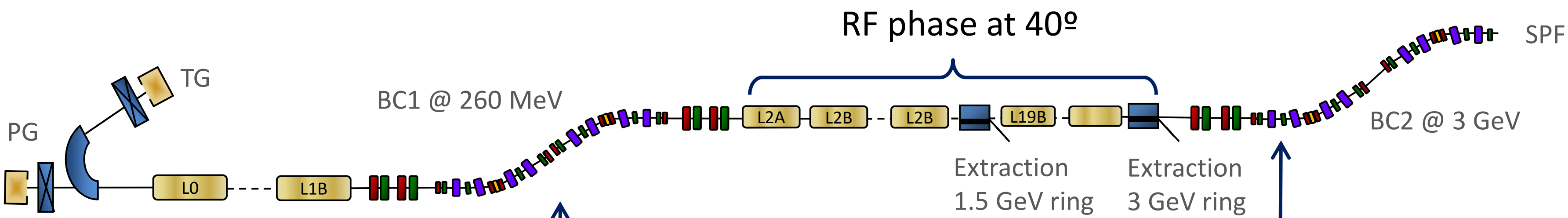
- positive fixed R56 (energy chirp from falling RF slope)
- natural T566 used for linearization, self-linearizing
- weak sextupoles at the center of each achromat used for fine tuning T566



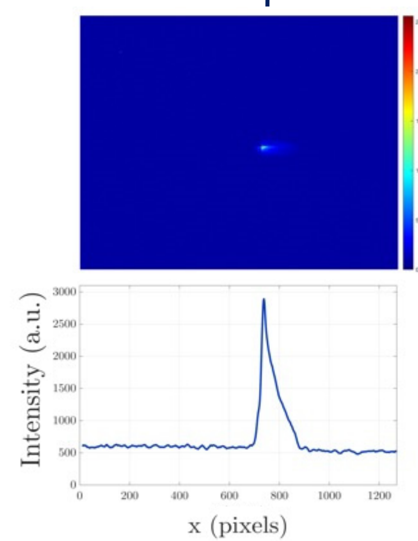
Zero-crossing method



Zero-crossing method



Sextupole strengths varied



Experimental results – linearly ramped current profiles

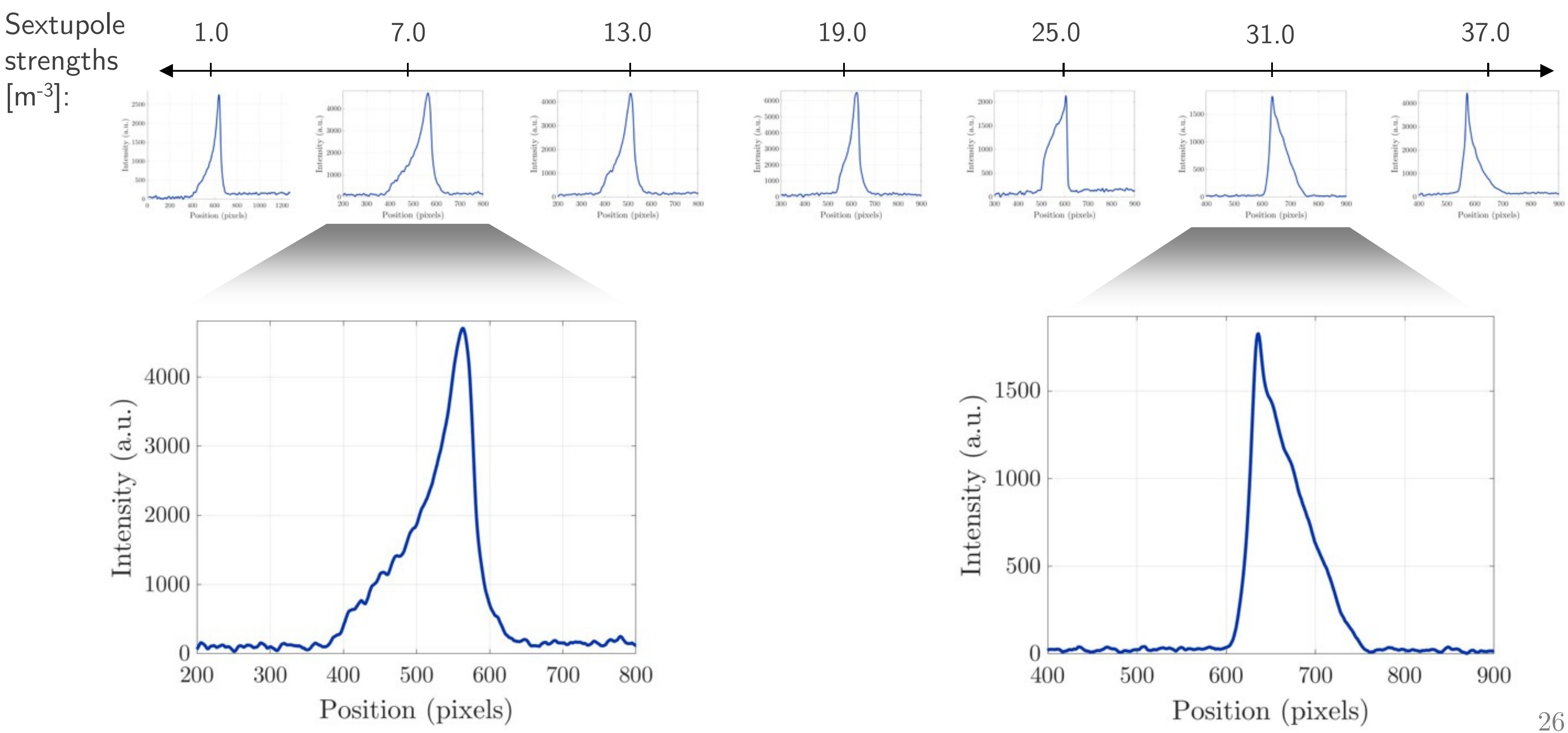
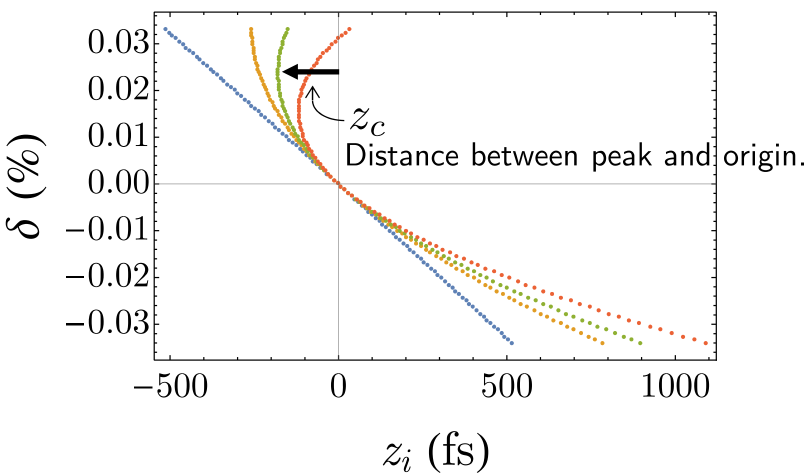


Illustration of compressed bunches



The origin is found as being the distance from one bunch edge to the position within the bunch where the accumulated integrated charge equals half of the total charge.

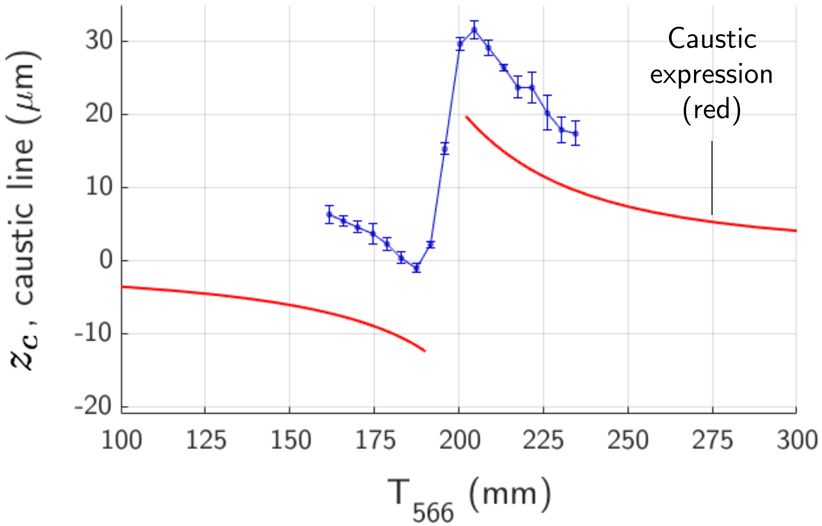
Caustic expression:

$$z_c(z_i) = -z_i - \frac{R_{56}\delta(z_i)}{2} + \frac{U_{5666}\ \delta^3(z_i)}{2} + \frac{\delta(z_i)}{2\delta'(z_i)}$$

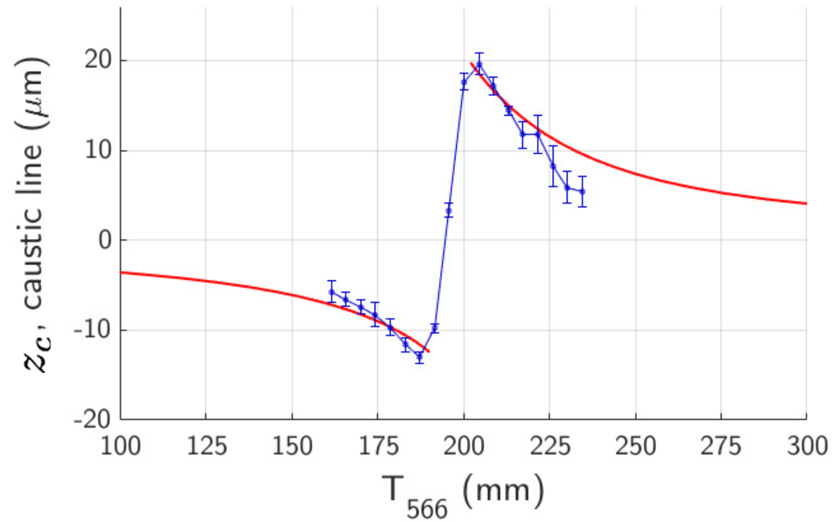
$$\tilde{T}_{566}(z_i) = \frac{1}{2\delta(z_i)}\left(-R_{56} - \frac{1}{\delta'(z_i)} - 3U_{5666}\ \delta^2(z_i)\right)$$

(Same expression as shown on slide 11, simply re-arranged)

Mapping out caustic lines

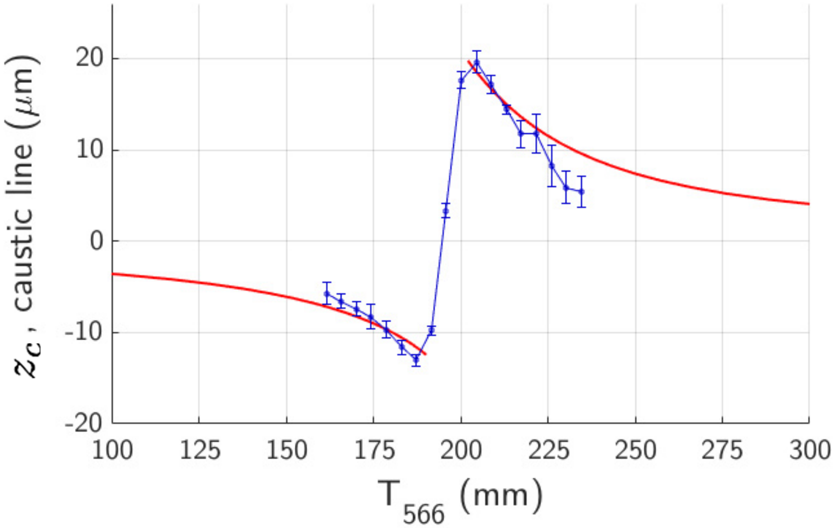


Offset removed



Offset due to the combined effects of wakefields and curvature of the phase space distribution.

Mapping out caustic lines



Offset of 14 micrometers removed

Where the caustic expression is undefined, the longitudinal phase space is considered well linearized, resulting in a short bunch with a symmetrical current profile.

$$z_c(z_i) = -z_i - \frac{R_{56}\delta(z_i)}{2} + \frac{U_{5666}\ \delta^3(z_i)}{2} + \frac{\delta(z_i)}{2\delta'(z_i)}$$

$$\tilde{T}_{566}(z_i) = \frac{1}{2\delta(z_i)}\left(-R_{56} - \frac{1}{\delta'(z_i)} - 3U_{5666}\ \delta^2(z_i)\right)$$

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Conclusions

- Caustics are a useful way that we can look at various types of focusing.
- Demonstration of current horn suppression through manipulation of the higher-order dispersion.
- Preliminary experimental results show good agreement in shape with the theory.
- In addition to validating the caustic expressions, these measurements demonstrate the effectiveness of optical linearization of the MAX IV bunch compressors.

Acknowledgements

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- Sara Thorin, Jonas Björklund Svensson, and Joel Andersson (MAX IV)
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- Mark Boland (Canadian Light Source)
- Peter Williams (Daresbury Laboratory)
- Dave Douglas (J-Lab)
- In memory of Greg LeBlanc (Australian Synchrotron)

Thank you