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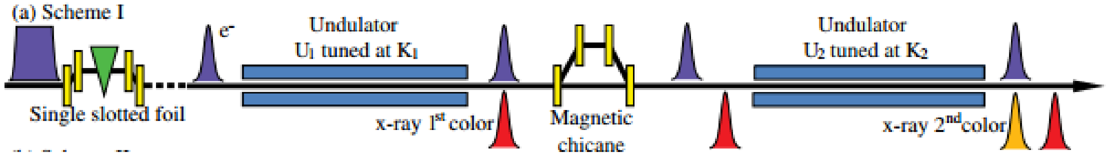
Two-Color Beam Generation via Wakefield Excitation

Outlook

- **Possible methods for two-color generation:**
  - Undulator K parameter tuning
  - Laser twin pulses
  - Fresh-slice
  - Seeding based schemes: laser wavelength of the seeding laser, crystal orientation
- **Wakefield based approach:**
  - Description of the method
  - Possible wakefield source
- **Tunability in time and energy separation among the two pulses**
- **Implementation at SwissFEL**
- **Future plans**
- **Conclusions**

Possible methods for two color generation

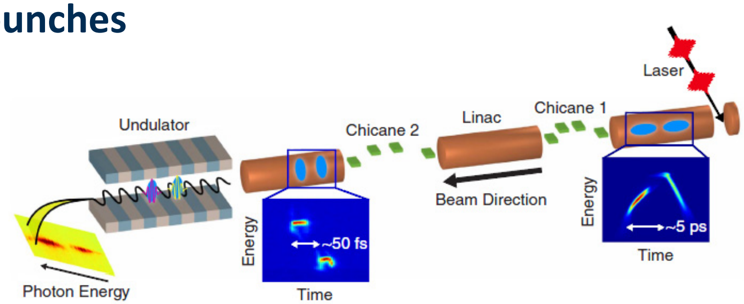
K parameter tuning method



- ❑ Some tunability
- ❑ Beam quality preservation
- ❑ Limited laser intensity

A. A. Lutman et al., *Experimental Demonstration of Femtosecond Two-Color X-Ray Free-Electron*, PRL **110**, 134801 (2013)

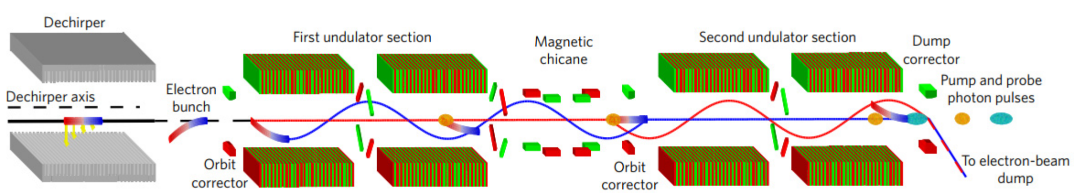
Laser twin bunches



- ❑ Some tunability
- ❑ Possible beam quality degradation
- ❑ Maximum laser intensity

A. Marinelli et al., *High-intensity double-pulse X-ray free-electron laser*, Nat. Comm. DOI: 10.1038/ncomms7369 (2013)

Fresh-slice scheme

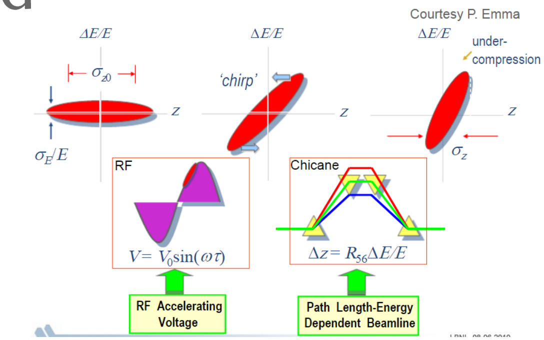


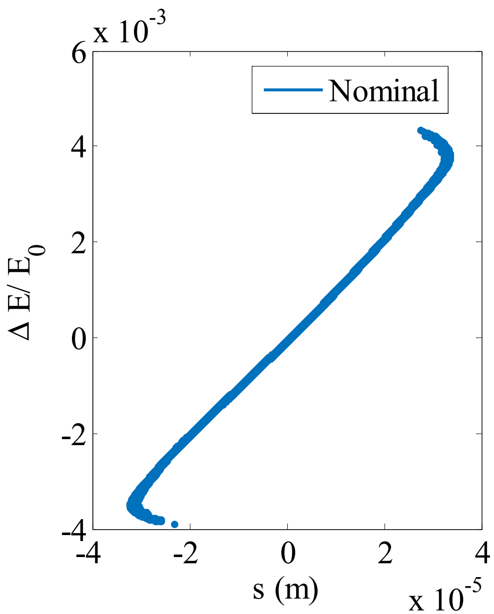
- ❑ Large tunability
- ❑ Beam quality preservation
- ❑ Limited laser intensity

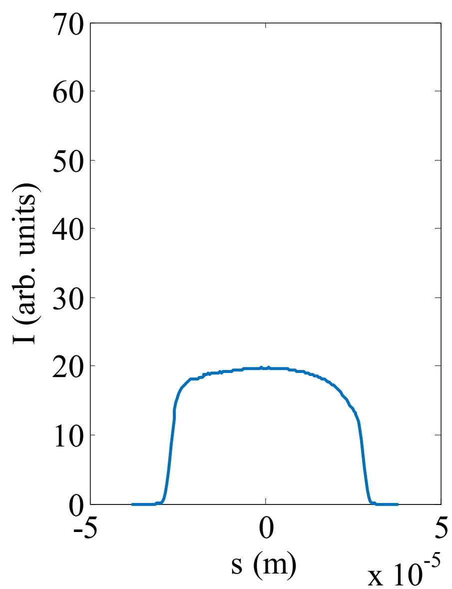
A. A. Lutman et al., *Fresh-slice multicolour X-ray free-electron lasers*, Nat. Phot. DOI: 10.1038/NPHOTON.2016.201 (2016)

Our approach: wakefield method

A well known and used way to compress the beam is to impose a (time,energy) correlation and to use the energy dependence of the trajectory in a dispersive section (typically chicane, dogleg).







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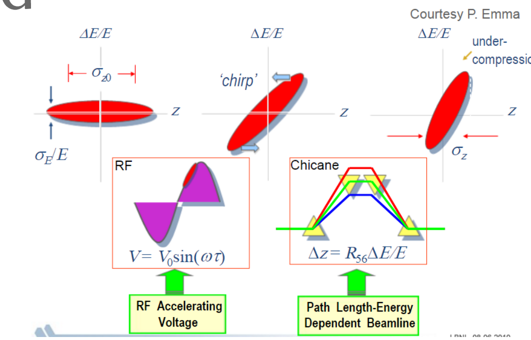
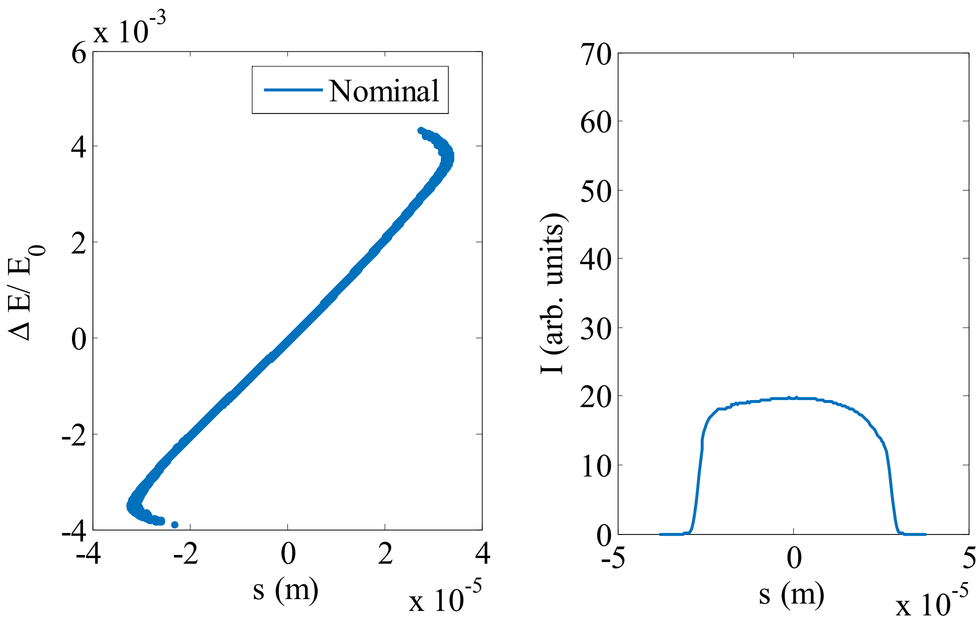


- Superimpose a (time,energy) correlation at two locations along the beam longitudinal phase space on top of the nominal chirp using a longitudinal wakefield
- In case the bunch length L_z and the wavelength of the wakefield λ_w are linked by the relation:

$$\lambda_W \approx L_z/2$$

- We obtain two sub-pulses compressing the beam in the downstream compression stages



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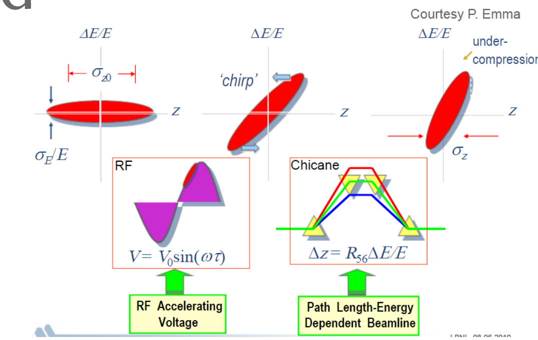

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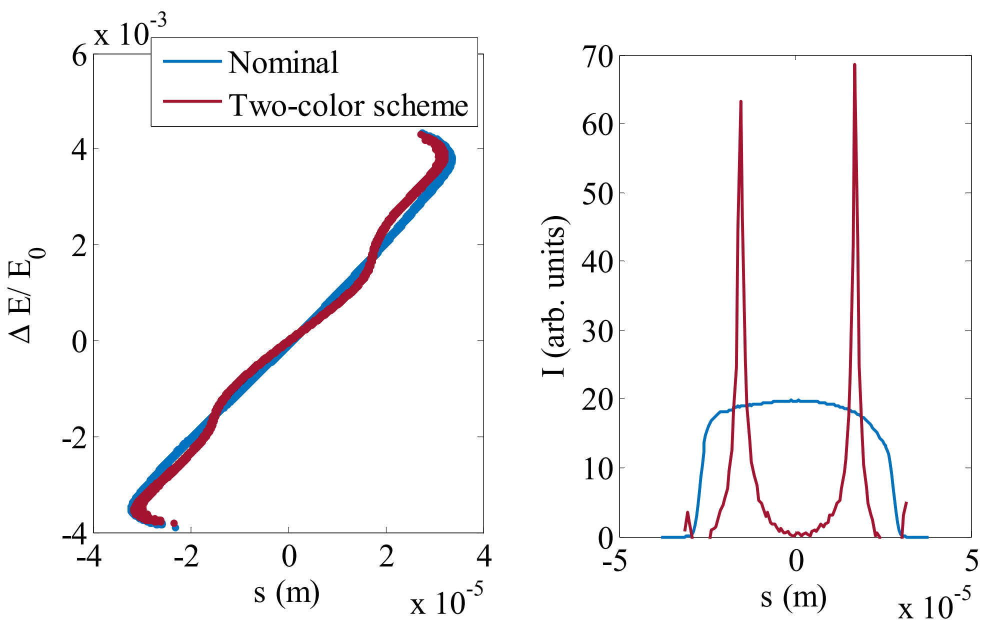
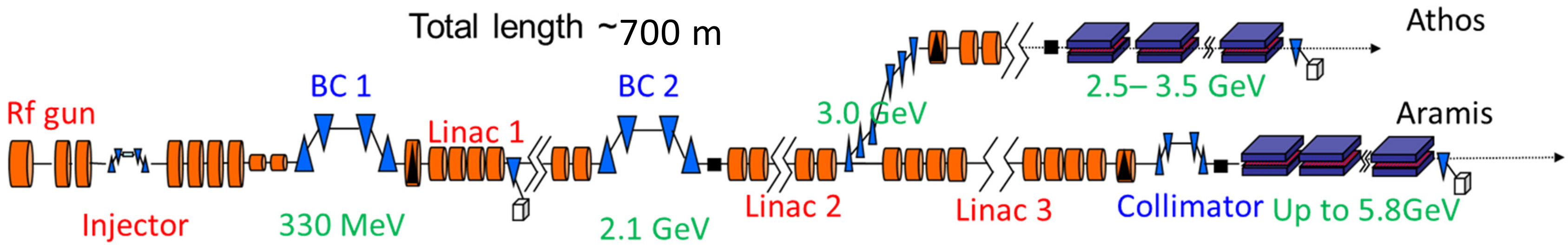


SwissFEL



Electron source

RF gun with CaF_2 laser driven with Cs_2Te photocathode

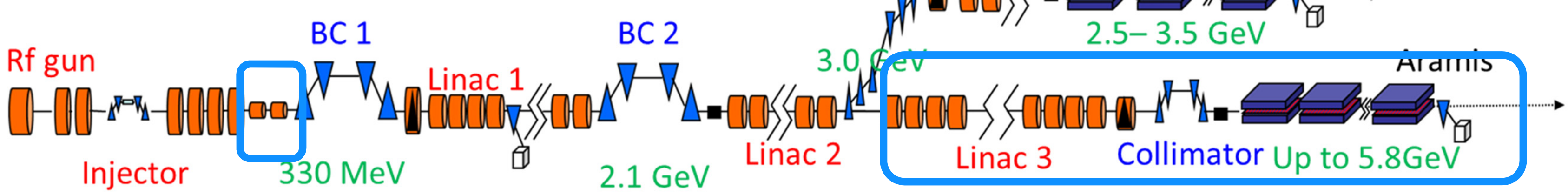
Undulator beamlines

1. **Aramis**: hard X-ray FEL (1-7 Å). In-vacuum, planar undulators with variable gap, period = 15 mm
2. **Athos**: soft X-ray FEL (6.5-50 Å). Undulators with variable gap and full polarization control, period = 38 mm

Wavelength	1 - 50 Å
Pulse duration	3 – 20 fs
Maximum e- beam energy	5.8 GeV
e- beam charge	10 – 200 pC
Repetition rate	100 Hz
Slice emittance (for the calculations assumed x2)	40 nm (10 pC) 150 nm (200 pC)
Slice energy spread	250-350 keV
Saturation length	< 50 m

- ❑ Construction started in 2013
- ❑ Commissioning started in Jul 2016
- ❑ Aramis user operation planned in Spring 2018
- ❑ Athos user operation planned in 2021

Wakefield source (relative energy spread)



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Suitable wakefield sources

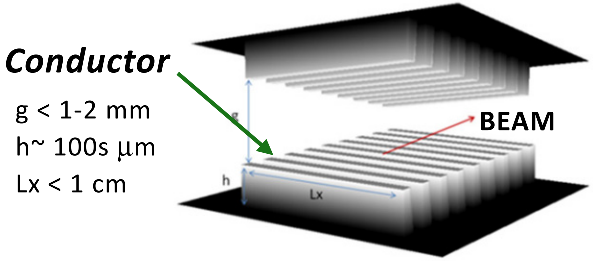
- Several sources can be considered. The requirements are:
  - Wavelength of the wakefield smaller than the full bunch length
  - Amplitude of the wakefield enough to limit the length of the device to a reasonable value (~few meters)

More typically corrugated →

Flat	Round
Easily tunable	More difficult to tune
Reduced amplitude (by $\pi^2/16$)	Maximum amplitude
Quadrupole component	Symmetric

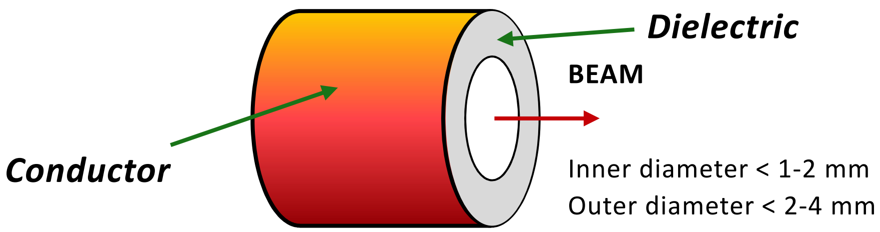
← More typically dielectric lined

CORRUGATED METALLIC



Typical wavelength ~ mm

DIELECTRIC LINED-WAVEGUIDE



Typical wavelength ~ 100s μm

Selected wakefield source

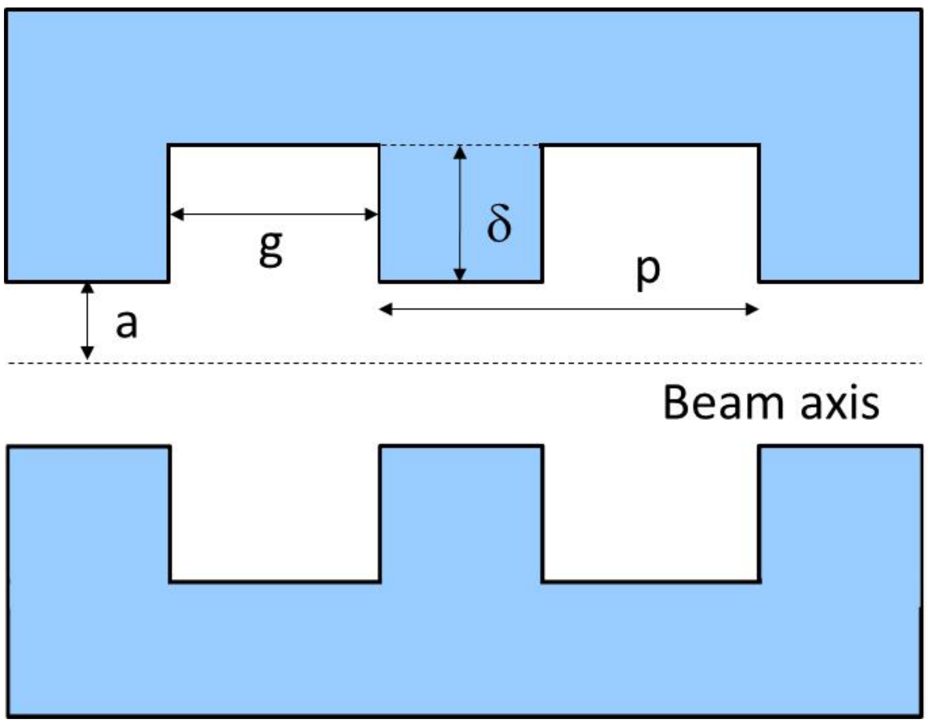
Typical full bunch length L_z upstream of the first compression stage of the order of few mm

Condition to have two sub-pulses:

$$\lambda_w \approx L_z/2$$

$\lambda_w \approx$mm

Corrugated metallic geometry selected, but equivalent with any other wakefield source respecting the condition on the left



The wakefield point charge is given by [1]:

$$w(s) \sim \frac{\pi}{16}\frac{Z_0 c}{\pi a^2} H(s) \cos\left(\frac{2\pi}{\lambda_W} s\right)$$

and the wavelength by:

$$\lambda_W = 2\pi\sqrt{\frac{a\delta g}{2p}}$$

[1] K. L. F. Bane and G. Stupakov, Report No. SLAC-PUB- 14925 (2013).

Geometry optimization

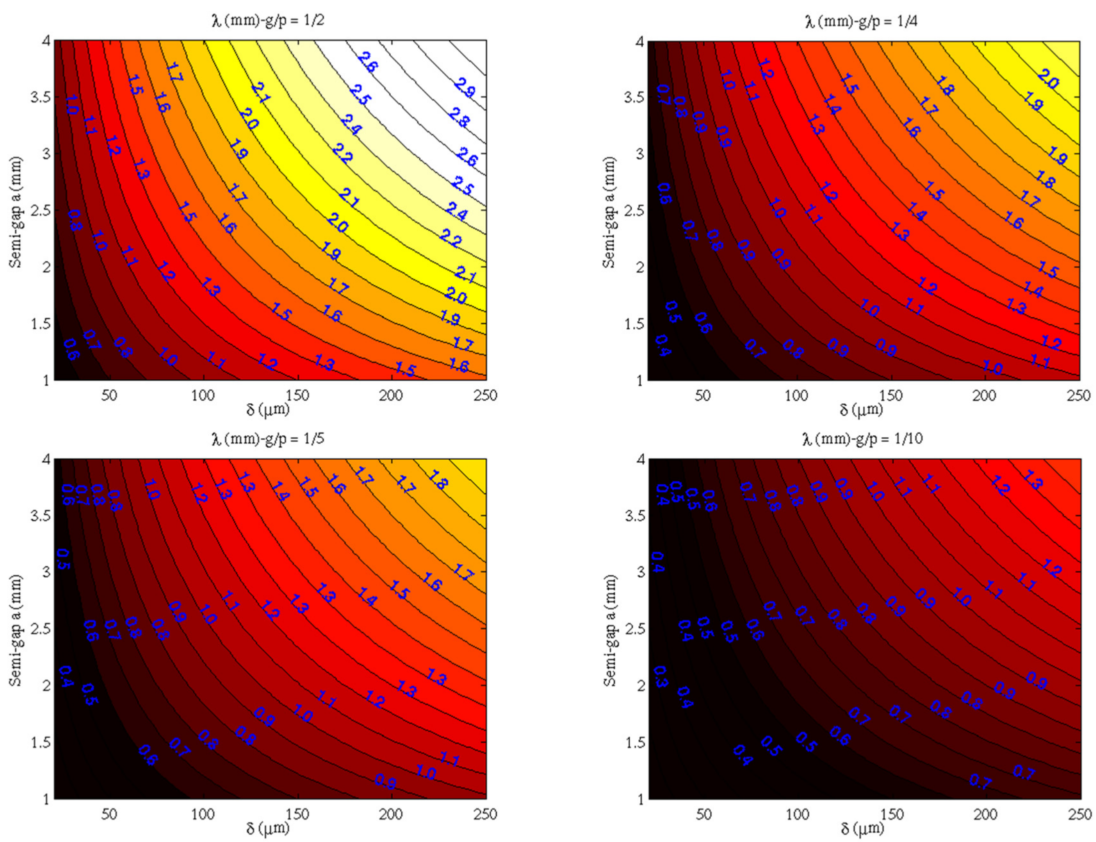
$$w(s) \sim \frac{\pi}{16}\frac{Z_0 c}{\pi a^2} H(s) \cos\left(\frac{2\pi}{\lambda} s\right)$$

The amplitude depends only on a

$$\lambda_W = 2\pi\sqrt{\frac{a\delta g}{2p}}$$

The wavelength depends on a combination of a and other geometry-parameters

There are **infinite** geometries **equivalent** from the beam dynamics point of view, once the product of a and $\delta g/p$ is constant (constant a)



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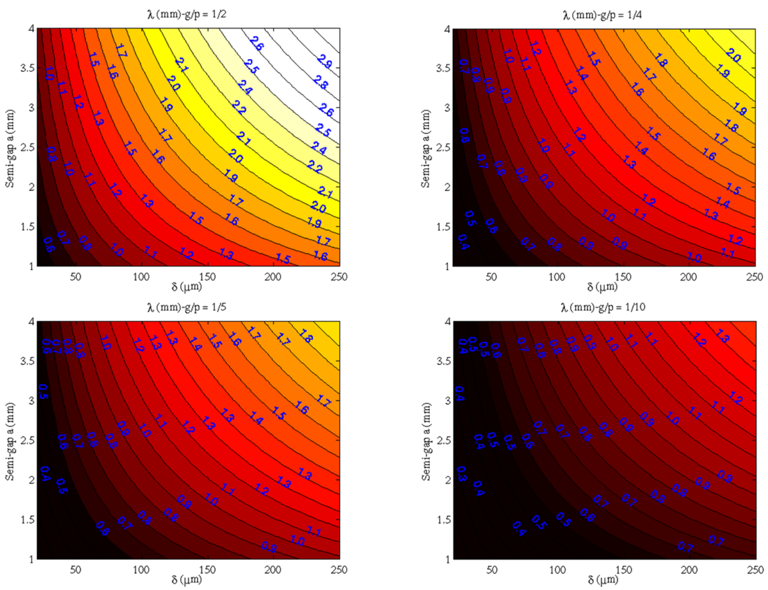
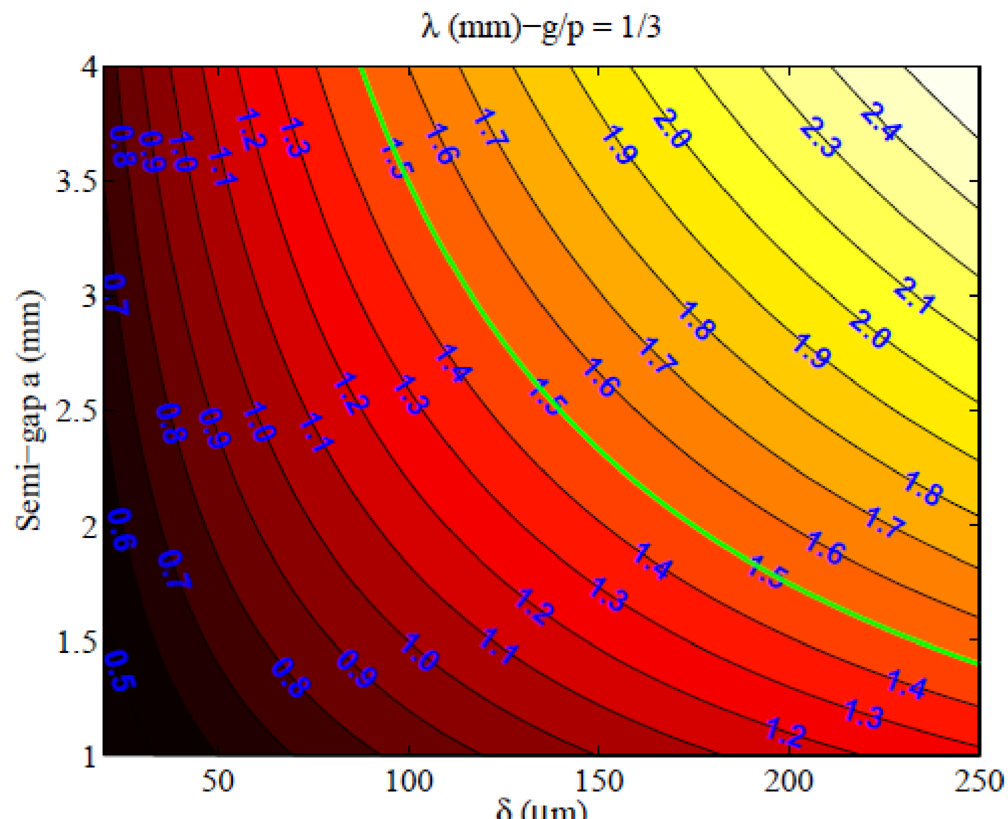
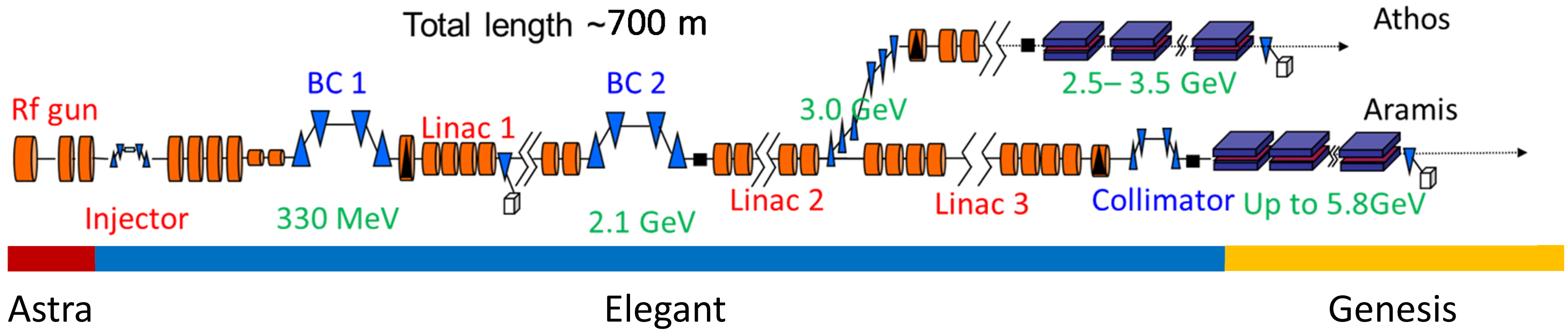
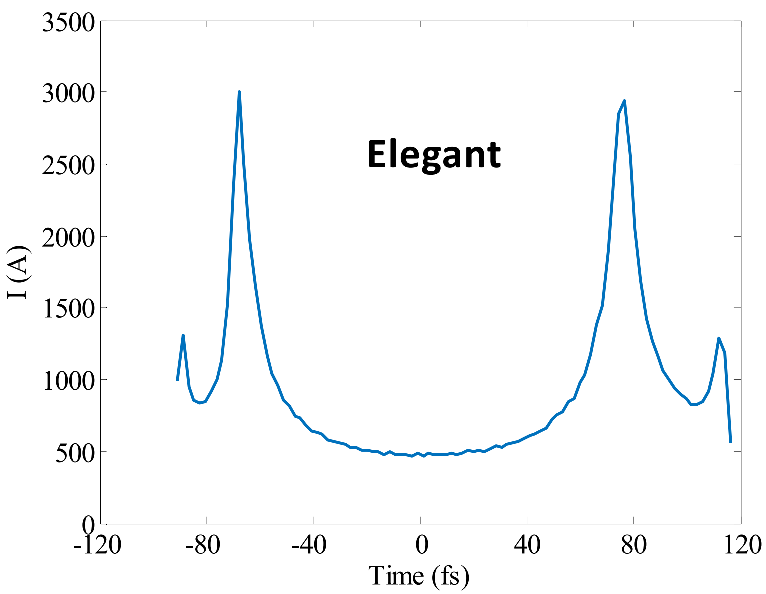


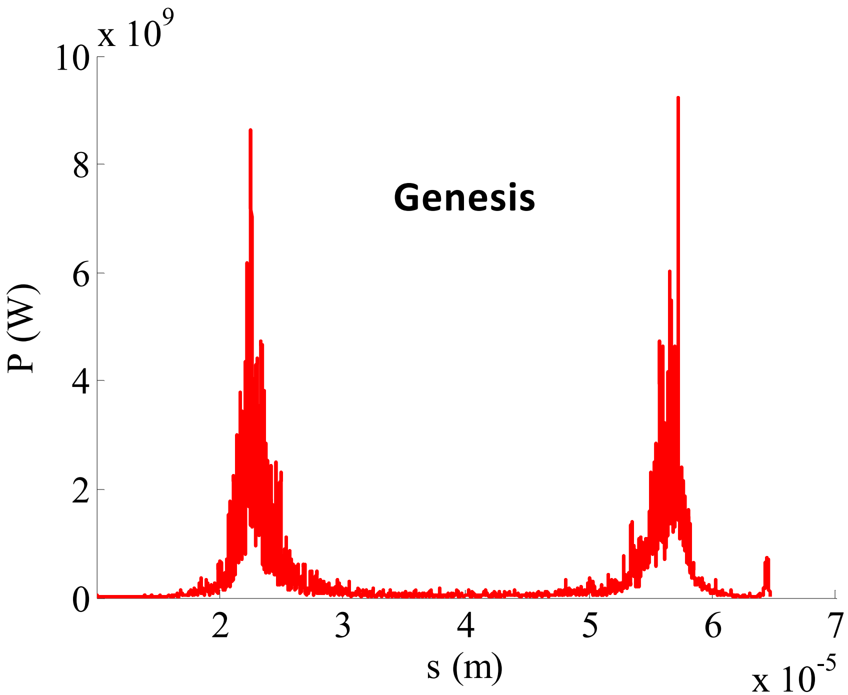
Parameter	Value
g (µm)	25
p (µm)	75
δ (µm)	170
Minimum a (mm)	1
a corresponding to $\lambda_W = 1.5$ mm ($L_z/2$) (mm)	2
L_P (m)	1.5



Start-to-end simulations







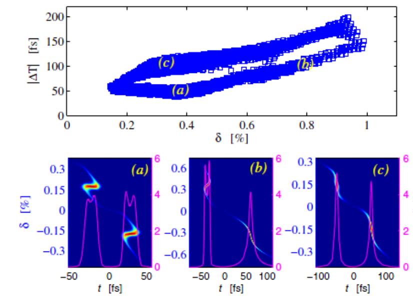
- Beam quality not modified → nominal SwissFEL laser power expected
- Relatively easy setup
- Intermediate difficult tuning

Time-energy tuning knobs: a la twin-bunch

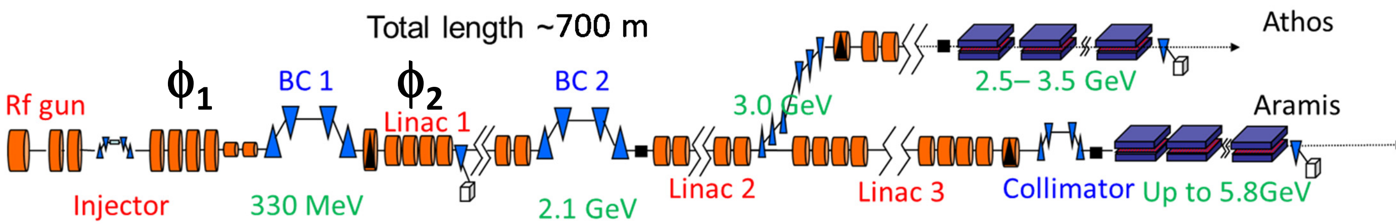
The bunch pattern in our case is similar to that of the twin-bunch scheme, therefore we may use in principle the same knobs

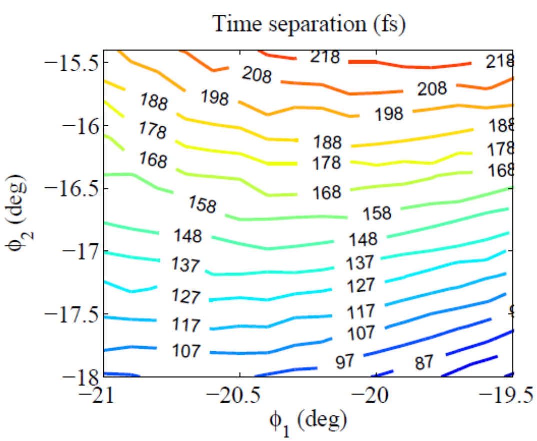
Twin-bunch scheme

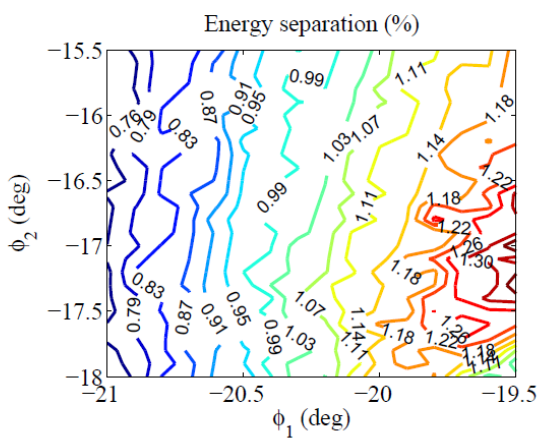
The time and energy separation among the two pulses is obtained changing the phases of the structures upstream and downstream the last bunch compressor [1]



Wakefield scheme







Tuning range determined by:

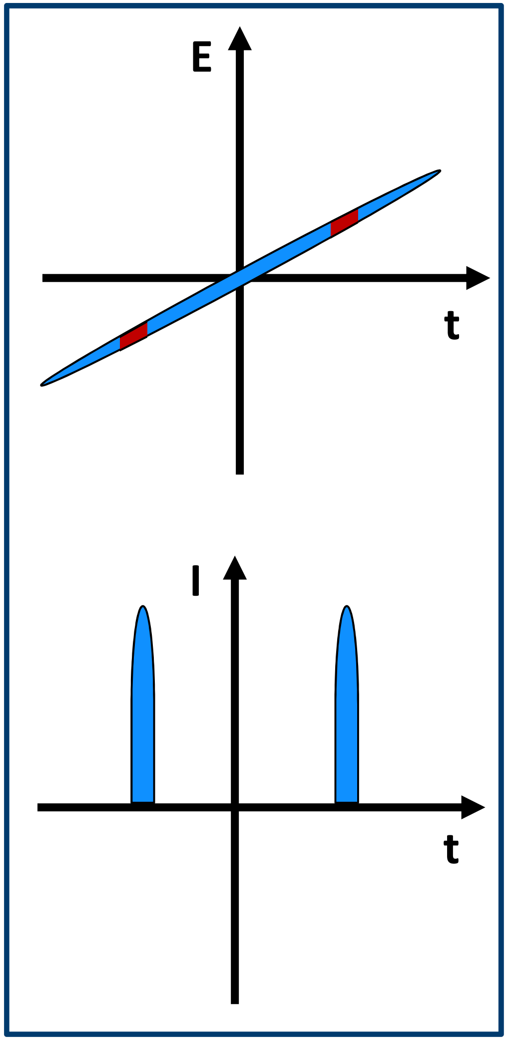
- ❑ Margin on the accelerating gradient in Linac 1 and Linac 2 (radiation wavelength)
- ❑ Tolerable peak current variation (radiation intensity)

[1] Z. Zhang, Y. Ding, A. Marinelli, Z. Huang, PRST-AB, 18, 030702 (2015).

Time-energy tuning knobs

Time separation

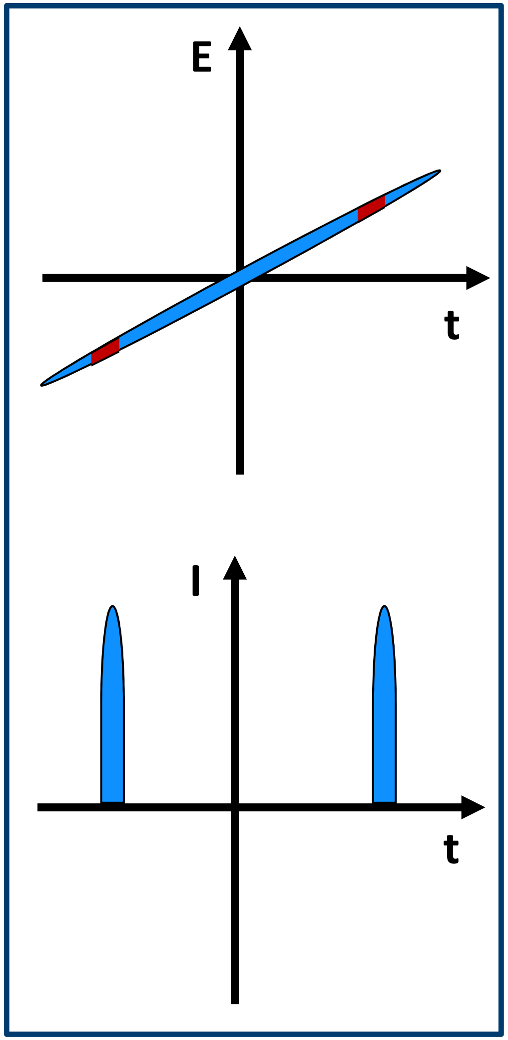
Energy separation



Time-energy tuning knobs

Time separation

Change λ_w of the corrugated plate



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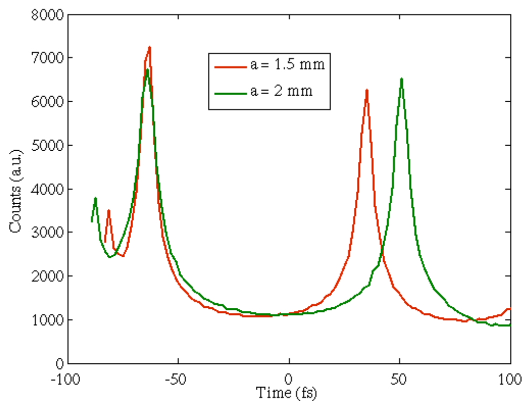

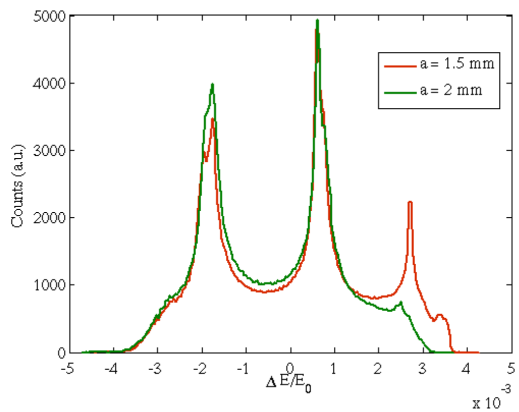

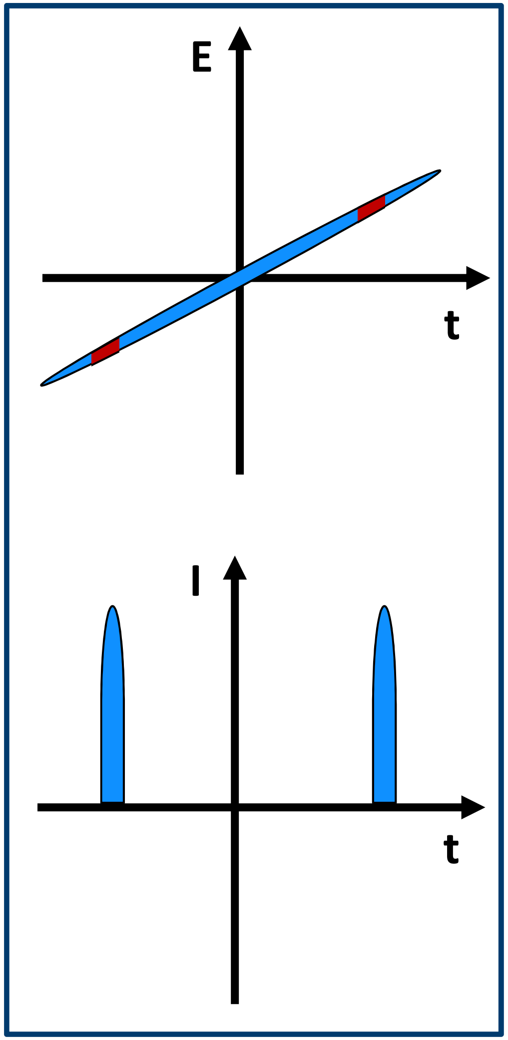

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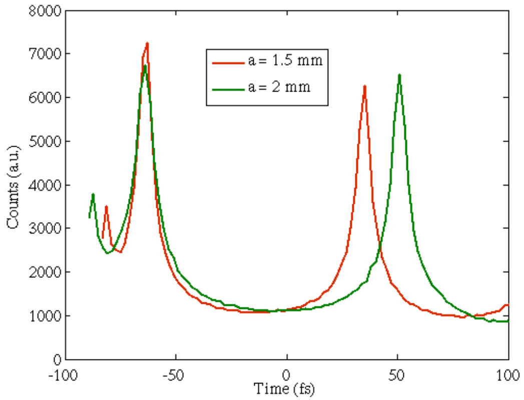
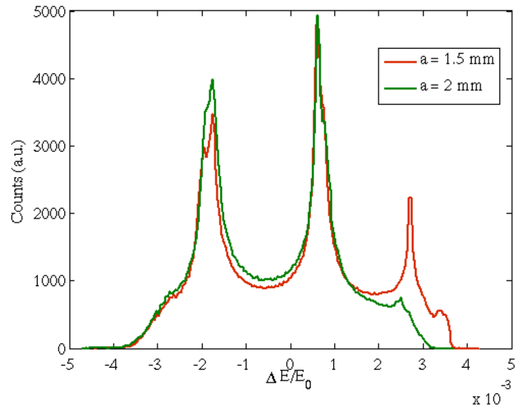
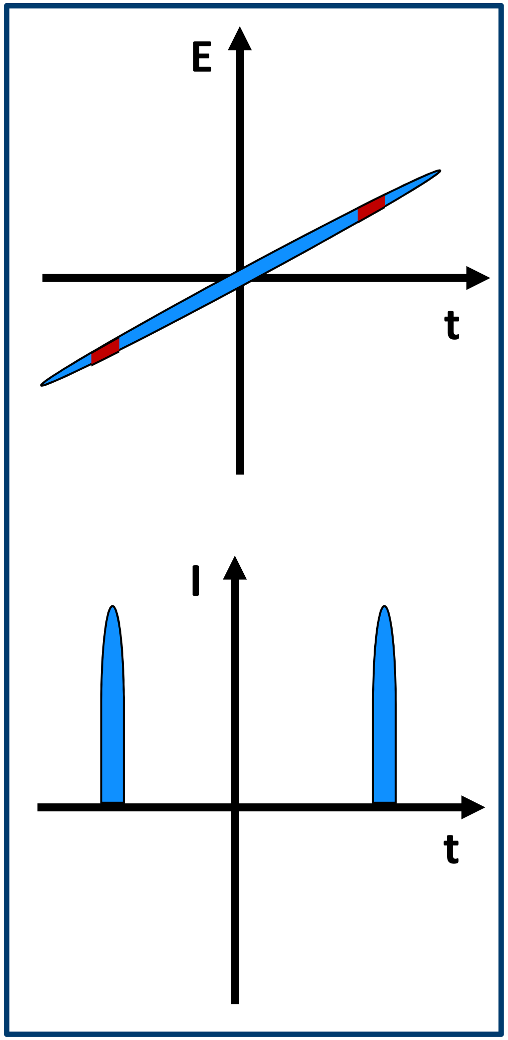






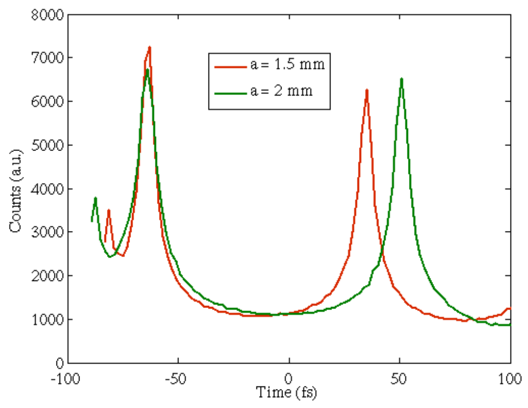
Energy separation

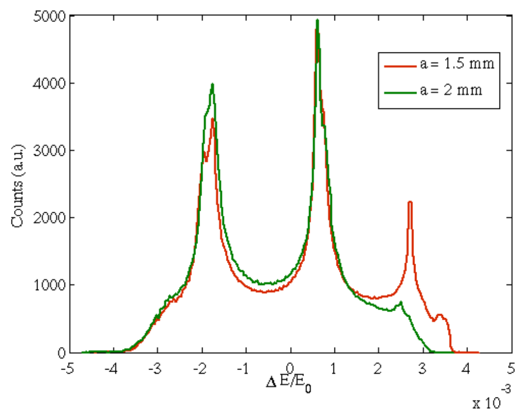
Vary the phase of the structures downstream of BC2

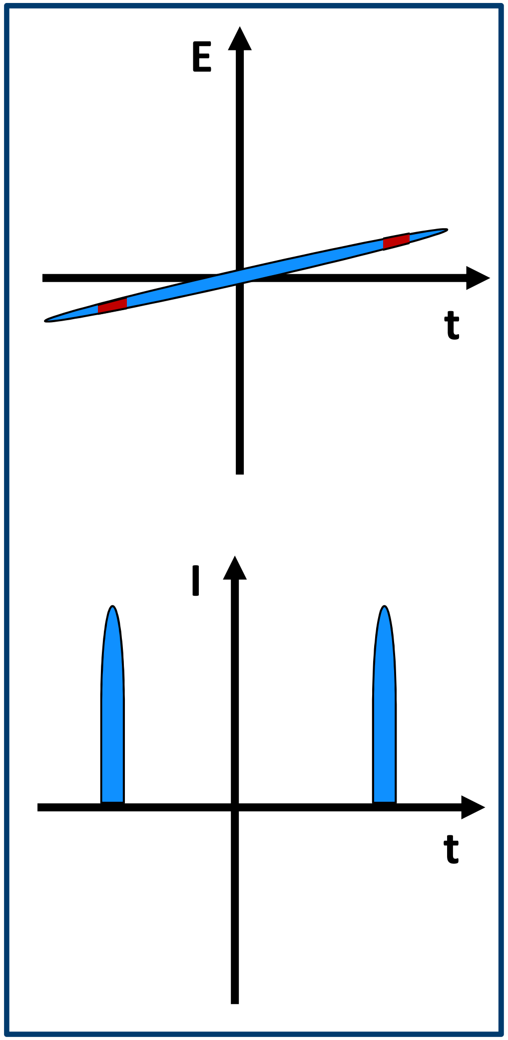
Time-energy tuning knobs

Time separation

Change λ_w of the corrugated plate







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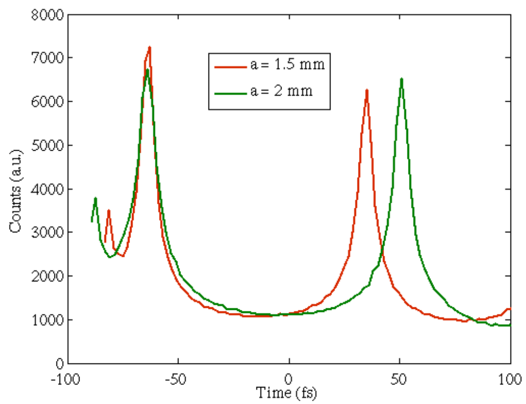

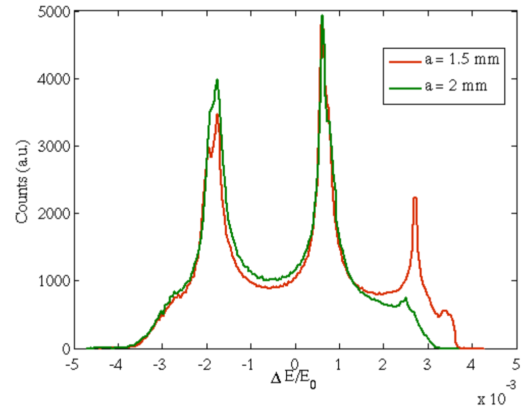

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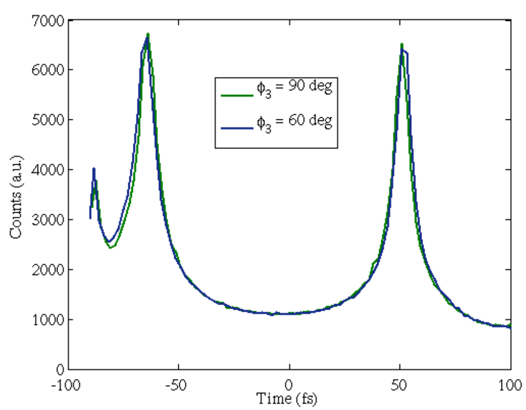
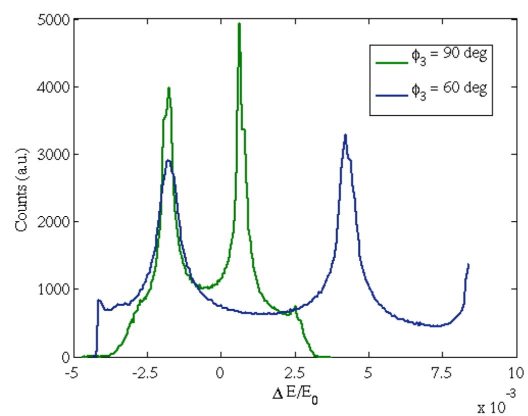
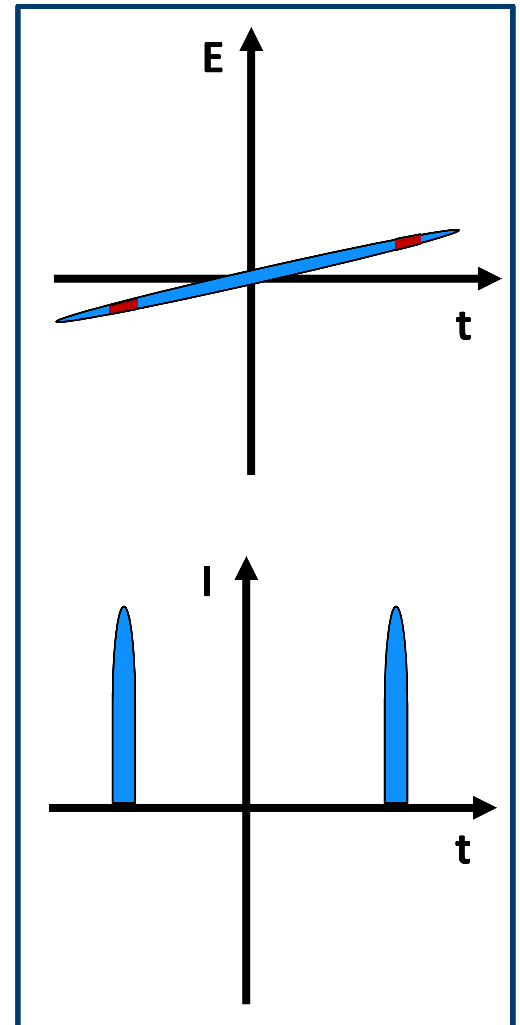
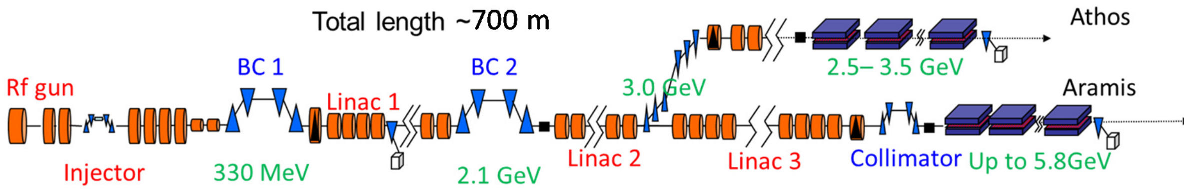






Expectation for SwissFEL



There are several constraints to be fulfilled during the tuning:

- ❑ Beam size at the corrugated structures
- ❑ Constant final electron bunch energy (limits of the cavity gradient)

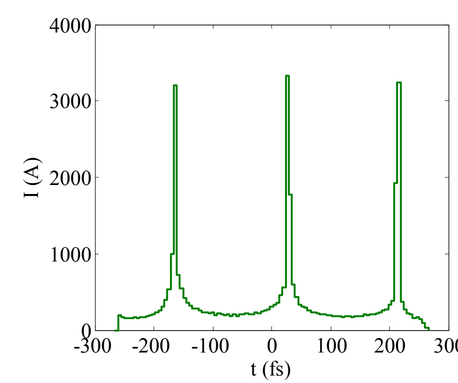
Maximum beam size (rms)	80 µm
Maximum $\Delta\phi$	58 degrees

	Δt (fs)	ΔE_{min} (%)	ΔE_{max} (%)
a = 1 mm, $\Delta\phi_3 = \pm 60°$	84	0.61	0.92
a = 1 mm, $\Delta\phi_3 = \pm 90°$	84	0.59	1.20
a = 2 mm, $\Delta\phi_3 = \pm 60°$	125	0.62	1.14
a = 2 mm, $\Delta\phi_3 = \pm 90°$	125	0.48	1.63
a = 1 mm, $\Delta\phi_3 = \pm 60°$, L = 1 m	188	0.37	0.93
a = 1 mm, $\Delta\phi_3 = \pm 90°$, L = 1 m	188	0.08	1.56
a = 1 mm, L = 1 m, first-third peaks, $\Delta\phi_3 = \pm 60°$	375	0.37	0.89

Furthermore…

A way to enhance and simplify the tunability:

- ❑ Generate multi-pulses



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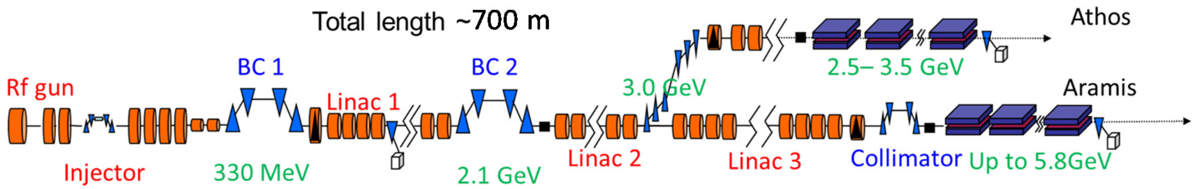

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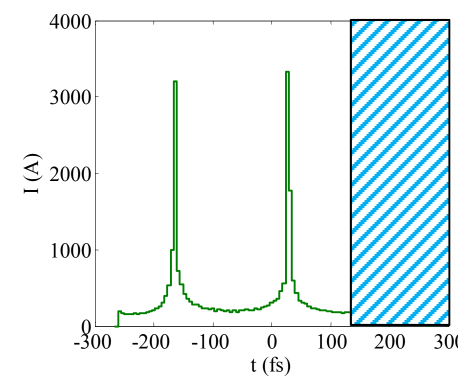
Furthermore…

A way to enhance and simplify the tunability:

- ❑ Generate multi-pulses
- ❑ Remove an external pulse (collimator)



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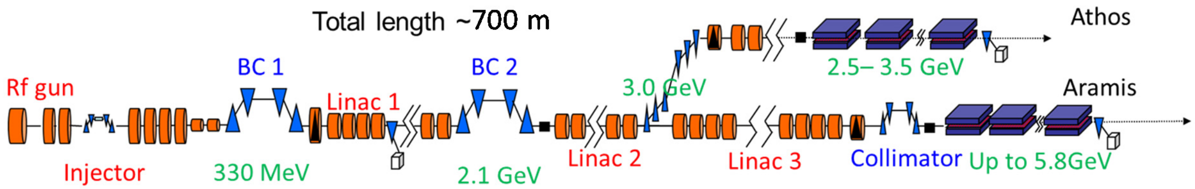

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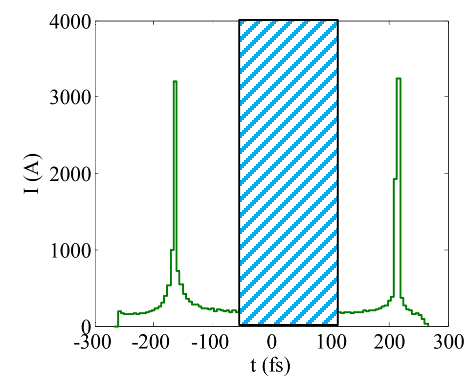
$a = 2$ mm, $\Delta\phi_3 = \pm 90°$	125	0.48	1.63
$a = 1$ mm, $\Delta\phi_3 = \pm 60°$, $L = 1$ m	188	0.37	0.93
$a = 1$ mm, $\Delta\phi_3 = \pm 90°$, $L = 1$ m	188	0.08	1.56
$a = 1$ mm, $L = 1$ m, first-third peaks, $\Delta\phi_3 = \pm 60°$	375	0.37	0.89

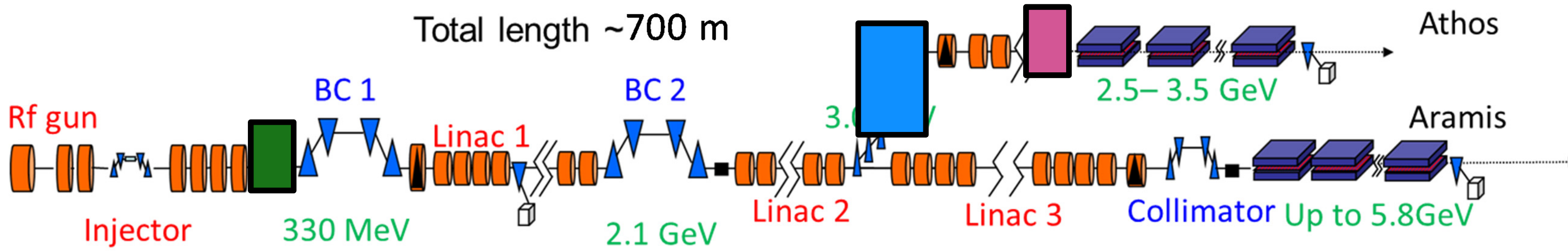
Furthermore…

A way to enhance and simplify the tunability:

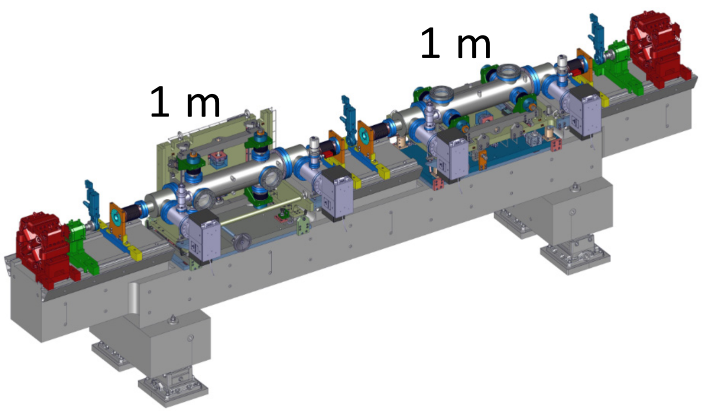
- ❑ Generate multi-pulses
- ❑ Remove an external pulse (collimator)
- ❑ Spoil the emittance of the central pulse (slotted foil or laser of the laser heater)

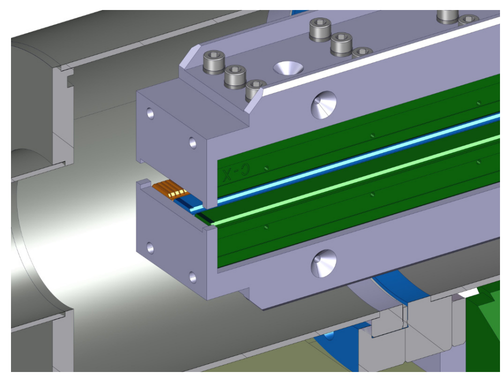


Next steps at SwissFEL: beam manipulation



- ❑ Passively streak the beam (1-10 ps bunch length) [1]: 1 mm ≤ λ_W ≤ 6 mm
- ❑ Test the two-color generation via wakefield excitation: λ_W = 1 mm
- ❑ Alternatively linearize (following idea in [2]): λ_W = 6 mm
- ❑ Remove the chirp residual from the compression [3], [4]: λ_W = 2 mm
- ❑ High intensity (hundreds of μJ) high frequency (up to 20 THz) THz source
- ❑ Passively streak the beam (~10-500 fs bunch length)





Assembly	Nov 2017
Delivery	Jan 2018
Operational	Jul 2018

[1] S. Bettoni, P. Craievich, A. A. Lutmann, M. Pedrozzi, PR-AB 19, 021304 (2016).

[2] P. Craievich, PRST-AB 13, 034401 (2010).

[3] P. Emma et al., PRL 112, 034801 (2014).

[4] S. Antipov, et al., PRL. 112, 114801 (2014).

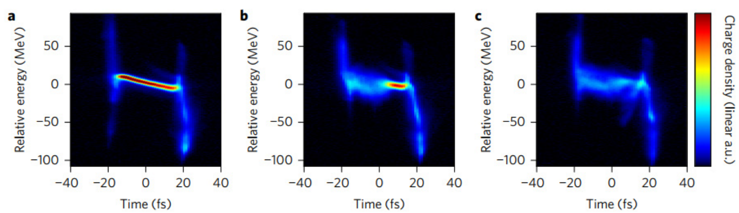
Future plans and possible synergies

Short bunches generation

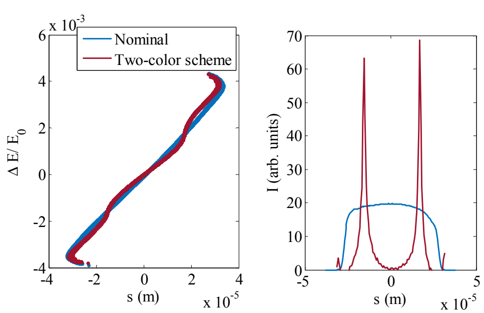
- $6 R 56$ (CSR)
- Efficient way to generate **short electron bunches** without increasing energy chirp (RF jitter) or R 5 56 56 (CSR)

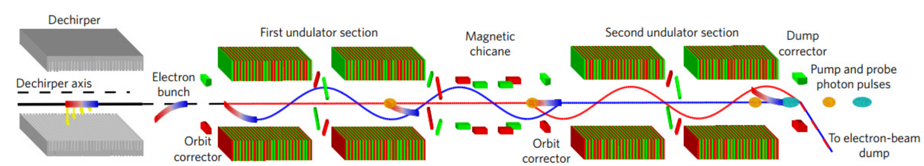
Synergy with the fresh slice scheme [1]

- In the fresh slice scheme the particles along the bunch get kicked with an angle **continuously** changing along the pulse
- The orbit is optimized to make the head or the tail lasing along different undulator sections



- We may use the two-color pulses generated with the wakefield to lase with the fresh slice scheme





- This would be an efficient way to control the **FEL pulse length**

[1] With A. Lutmann, under discussion

Conclusions

- Possible to use a wakefield source to generate two sub-pulses

- This method compared to others:

Pros:

- Gives full laser **intensity** with the given length of the undulator line
- Gives a **synchronization** among the two sub-pulses
- Is relatively easy to be implemented in the machine
- Allows a certain **tunability** of the sub-pulses in time and energy
- Possible **synergy** with another scheme to improve the FEL pulse length control

Cons:

- Additional **hardware** has to be installed compared to that of the standard FEL facility
- Intermediate range of **tunability** compared to other methods

- Performances for the SwissFEL case discussed

- More or less future activities based on passive devices at SwissFEL also sketched

More details in PR AB 19, 50702 (2016)

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PAUL SCHERRER INSTITUT PSI

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