A post Undulator X-band TDS for XFEL

Bolko Beutner, 23.02.23

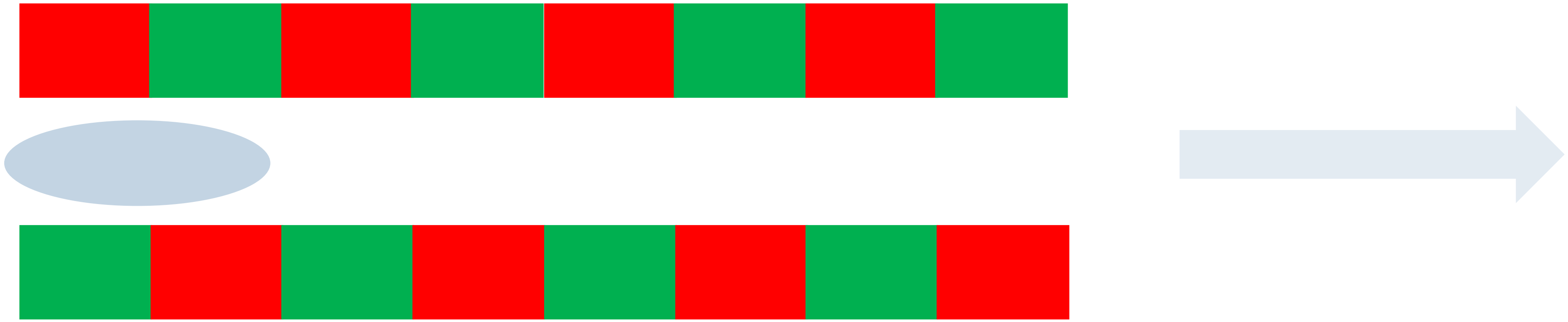
DESY. HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

European XFEL

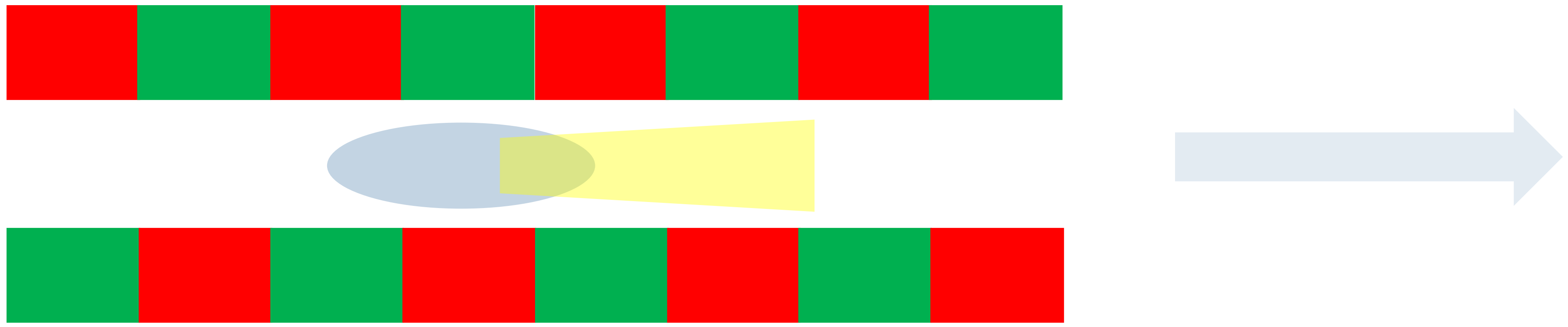
Overview

- Introduction
  - FEL Process
  - Corrugated structure - passive streaker “Dechirper”
  - Transverse deflecting structure
- PolariX
- Design Overview
- Summary

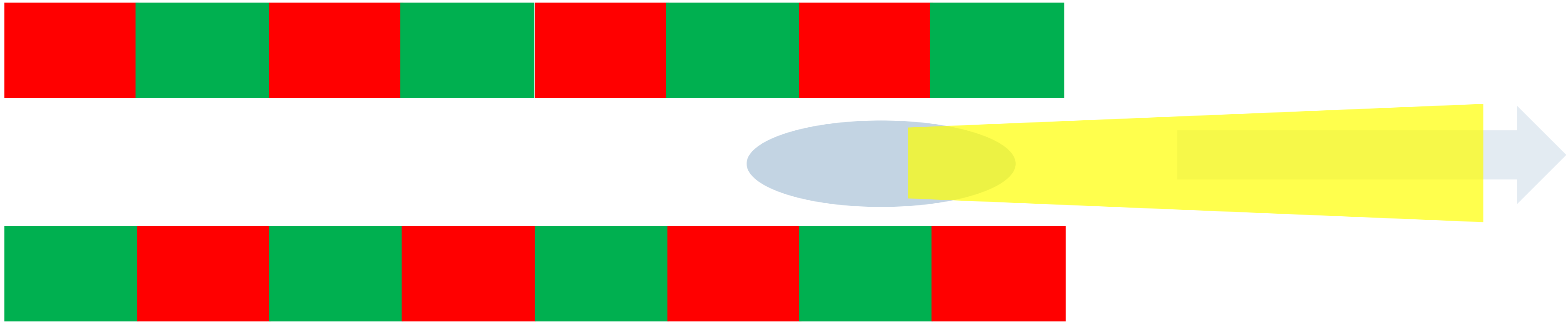
FEL Cartoon



FEL Cartoon



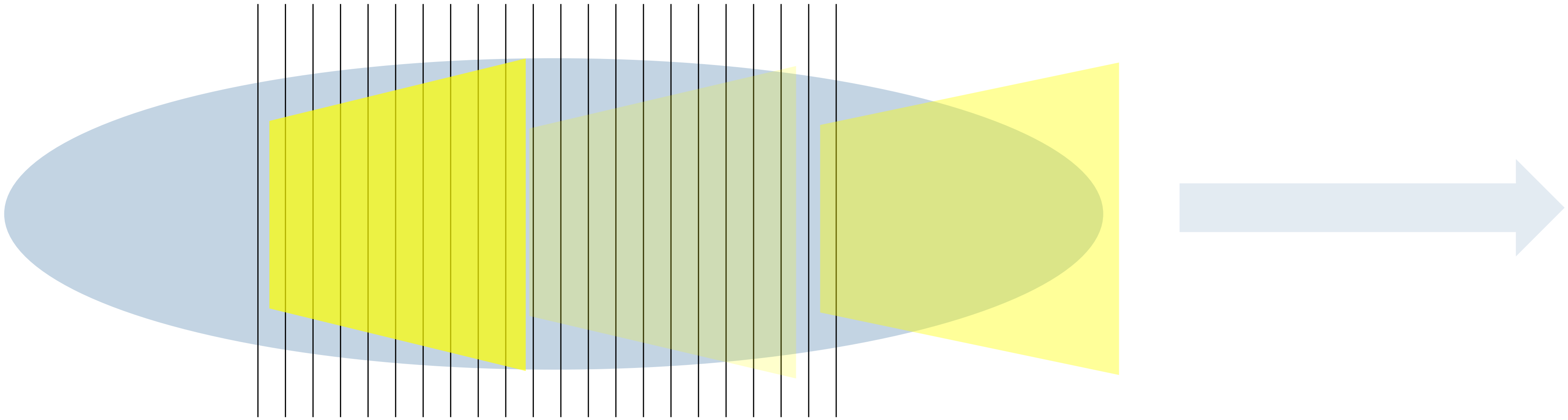
FEL Cartoon



FEL Cartoon

- FEL radiation is different in different parts of the bunch

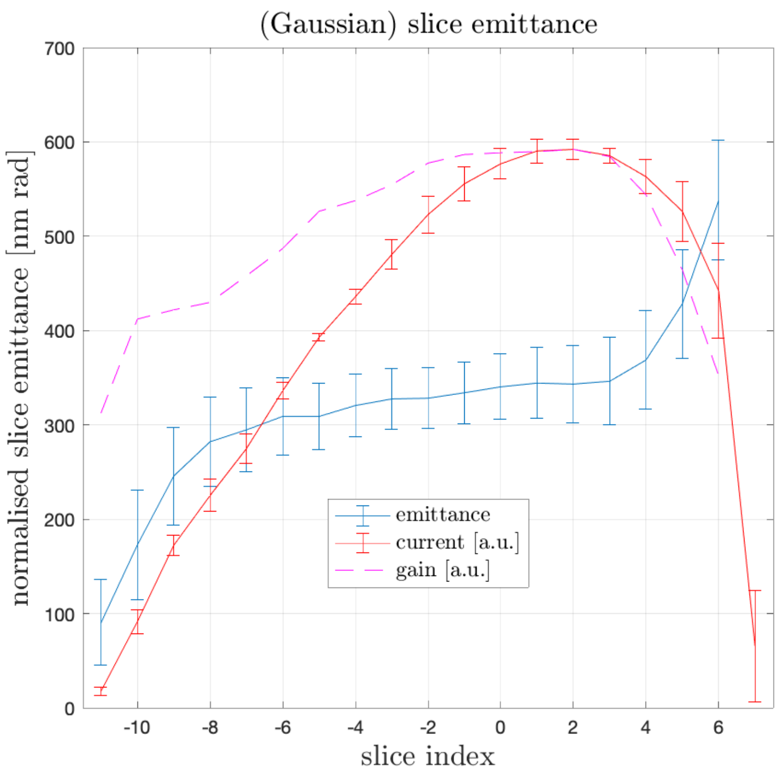
FEL Cartoon



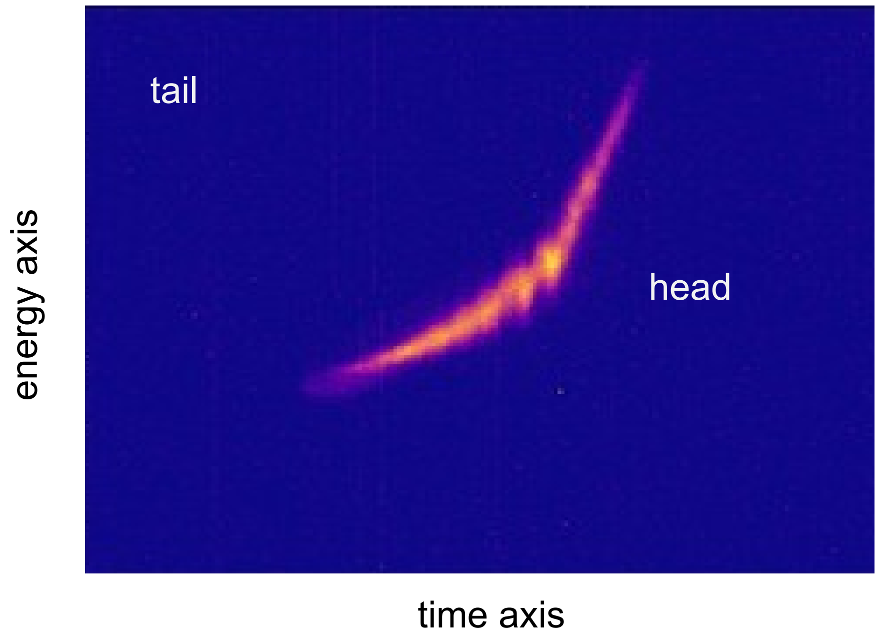
- lasing in slices (cooperation length) – typical hundreds or thousand of slices (image not to scale)
- Radiation from each slice depends on **alignment**, **emittance, energy spread**, and **charge**
- The more one slice radiates the more energy it looses and the **energy spread** increases!

Beam properties

- Charge and emittance is varying along the bunch especially due to bunch compression configuration



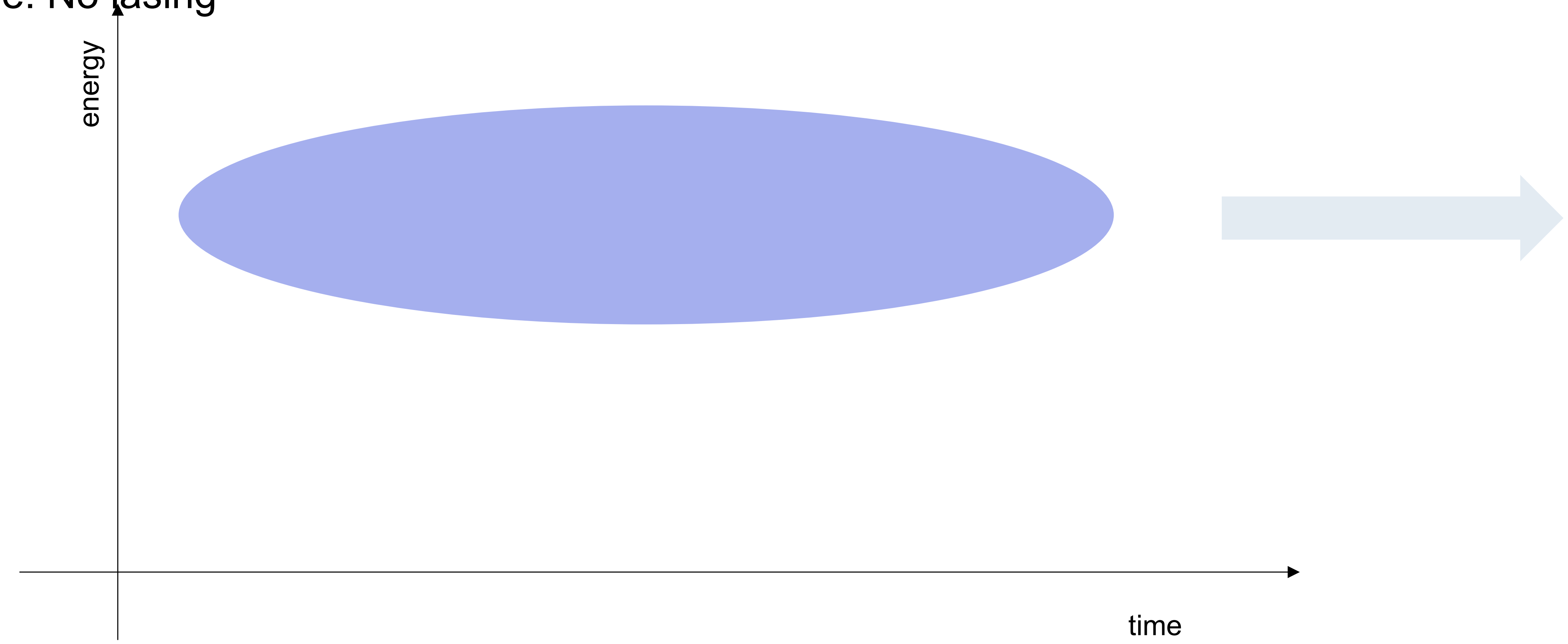
Longitudinal phase-space



- Beam energy and energy spread along the bunch is summarised in the **lognitudinal phase-space**

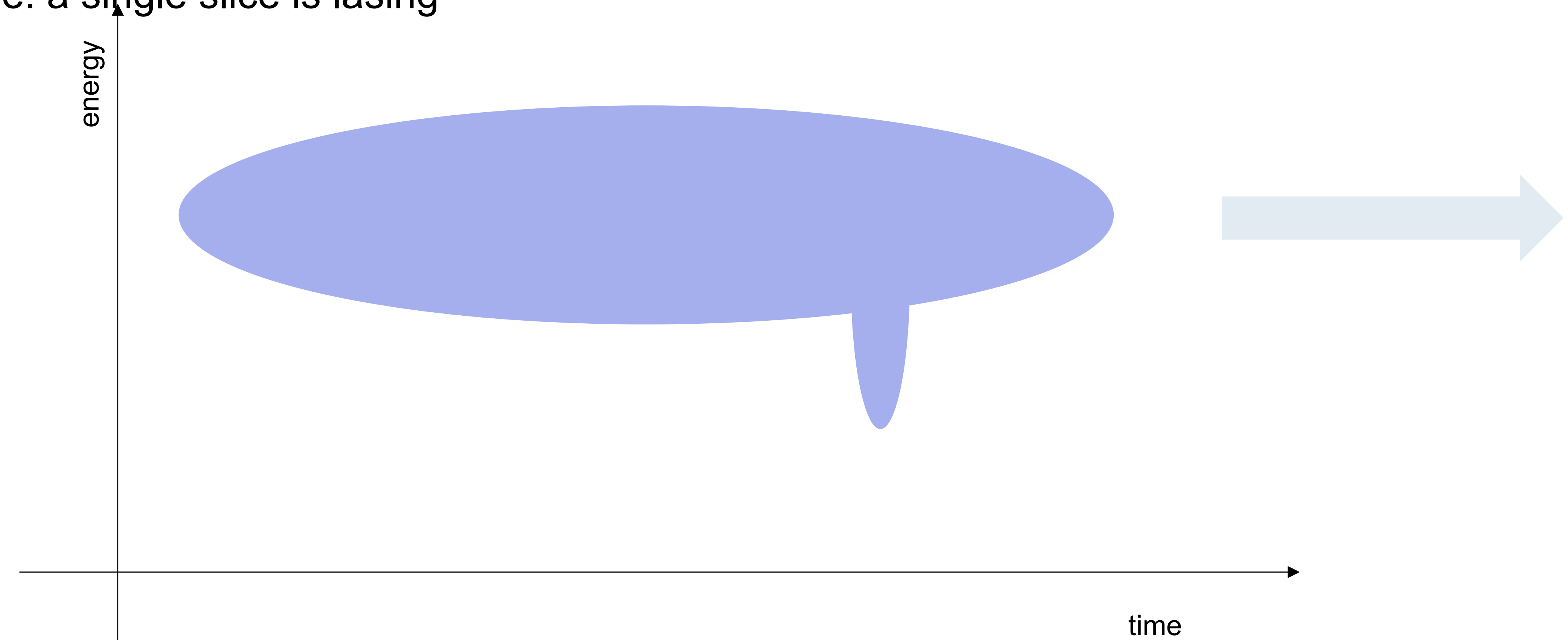
Longitudinal phase space

- Example: No lasing



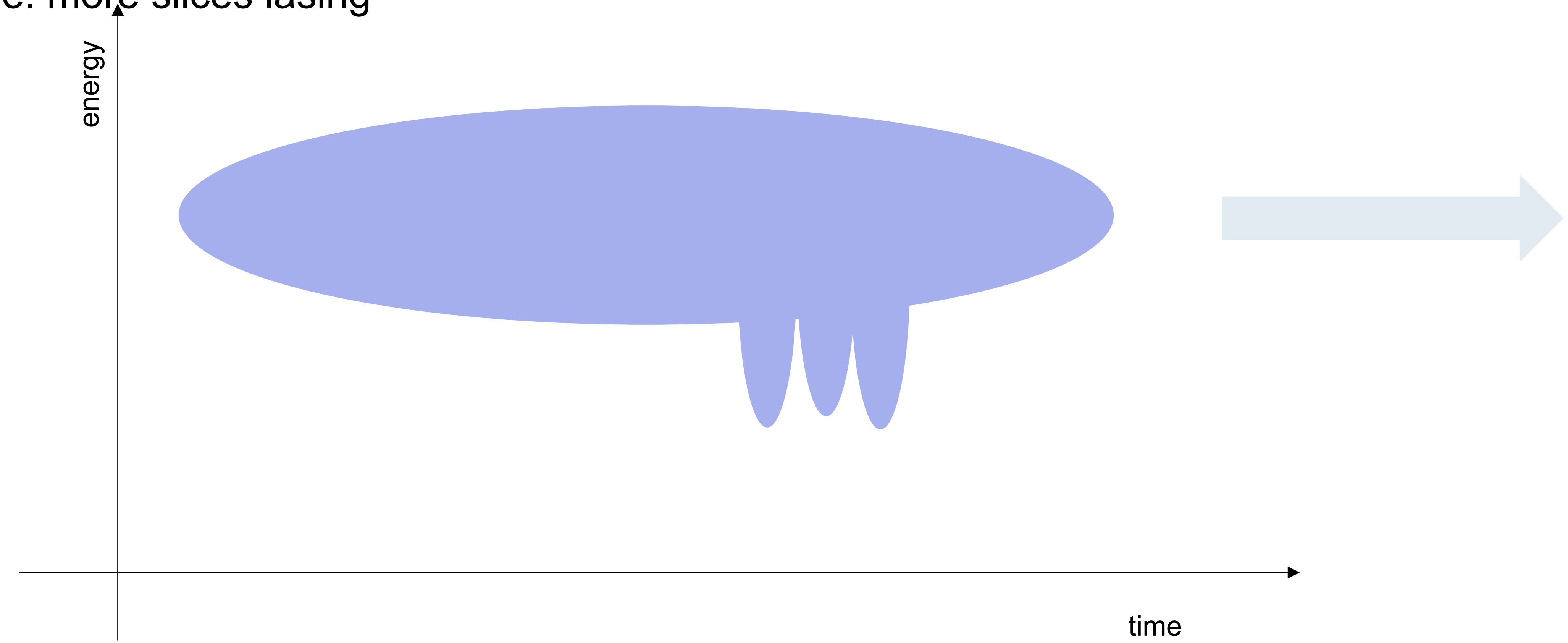
Longitudinal phase space

- Example: a single slice is lasing



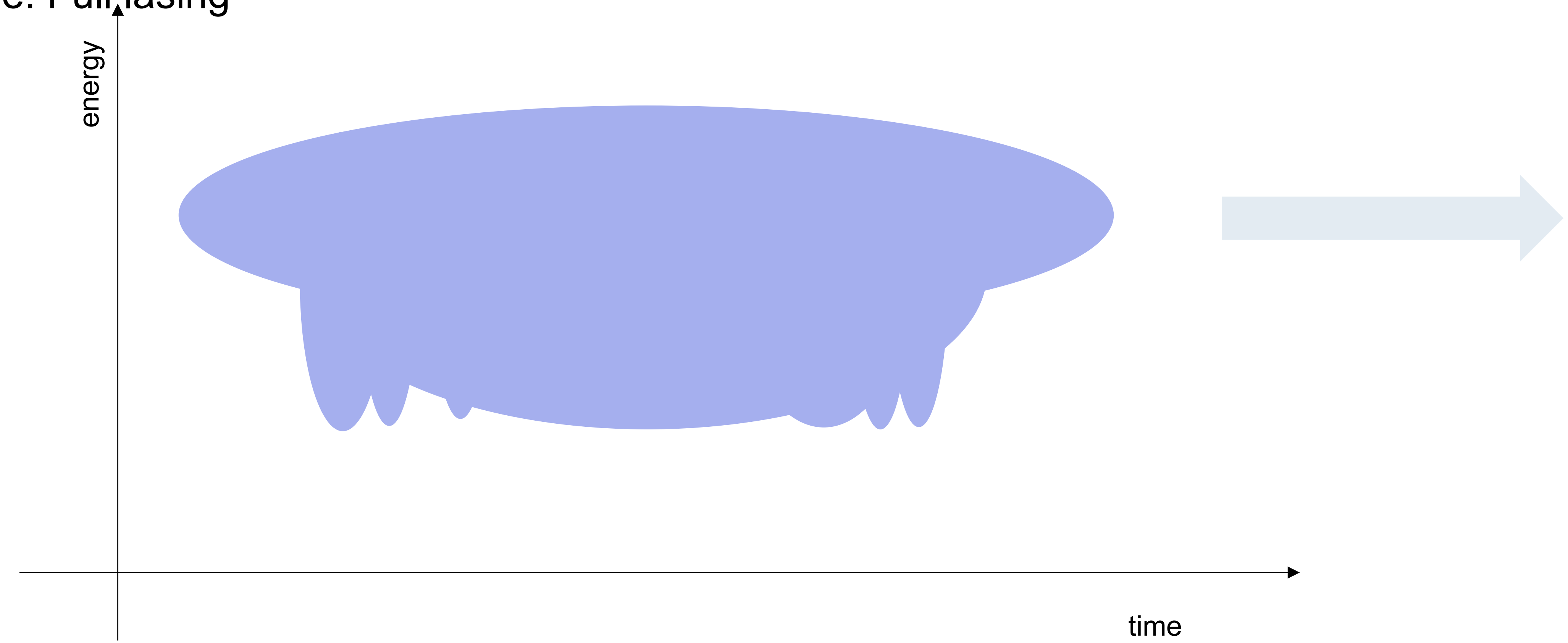
Longitudinal phase space

- Example: more slices lasing



Longitudinal phase space

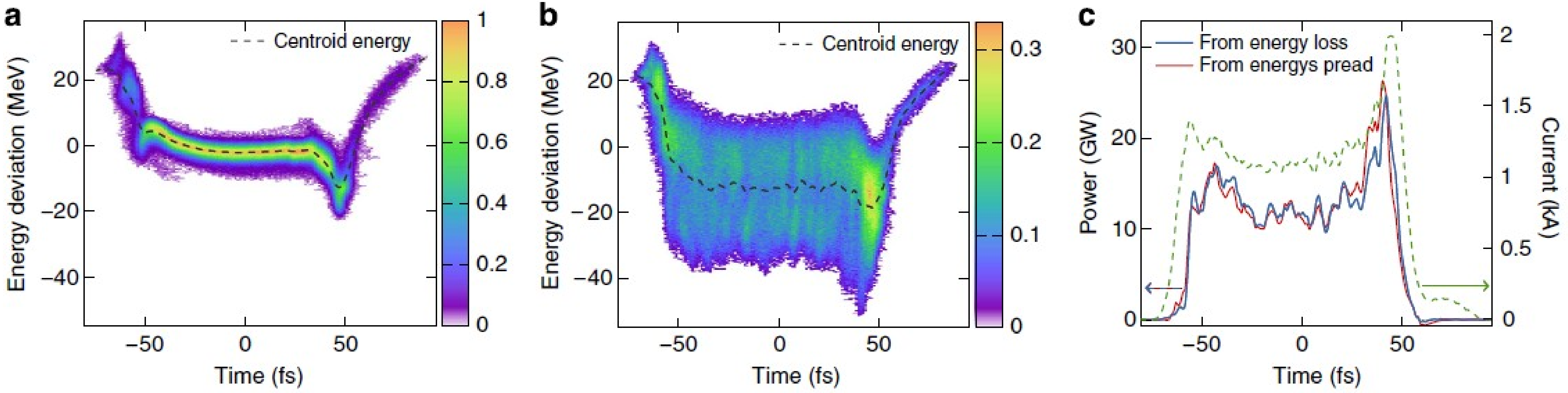
- Example: Full lasing



Measurement of longitudinal phase-space after lasing

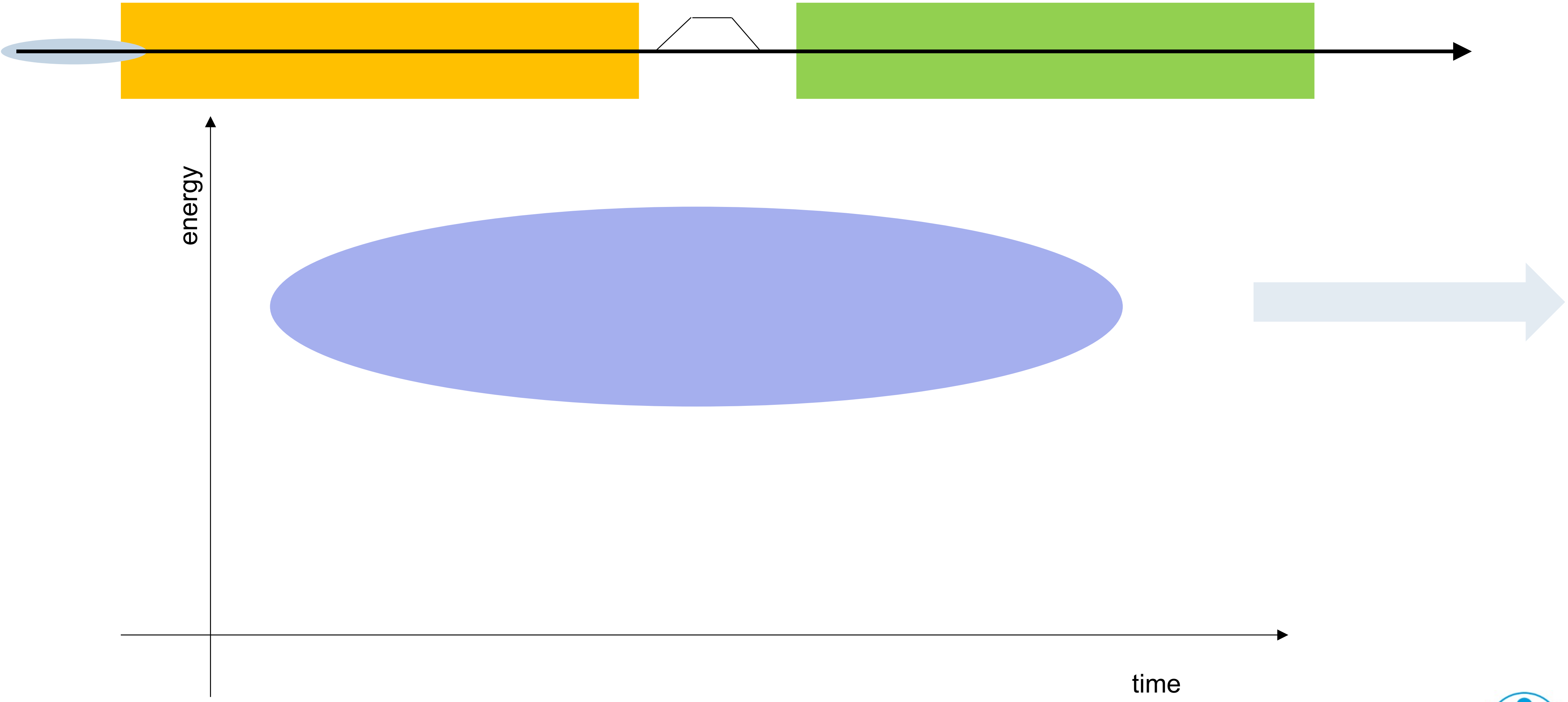
- Example: LCLS

Example LCLS: DOI: 10.1038/ncomms4762



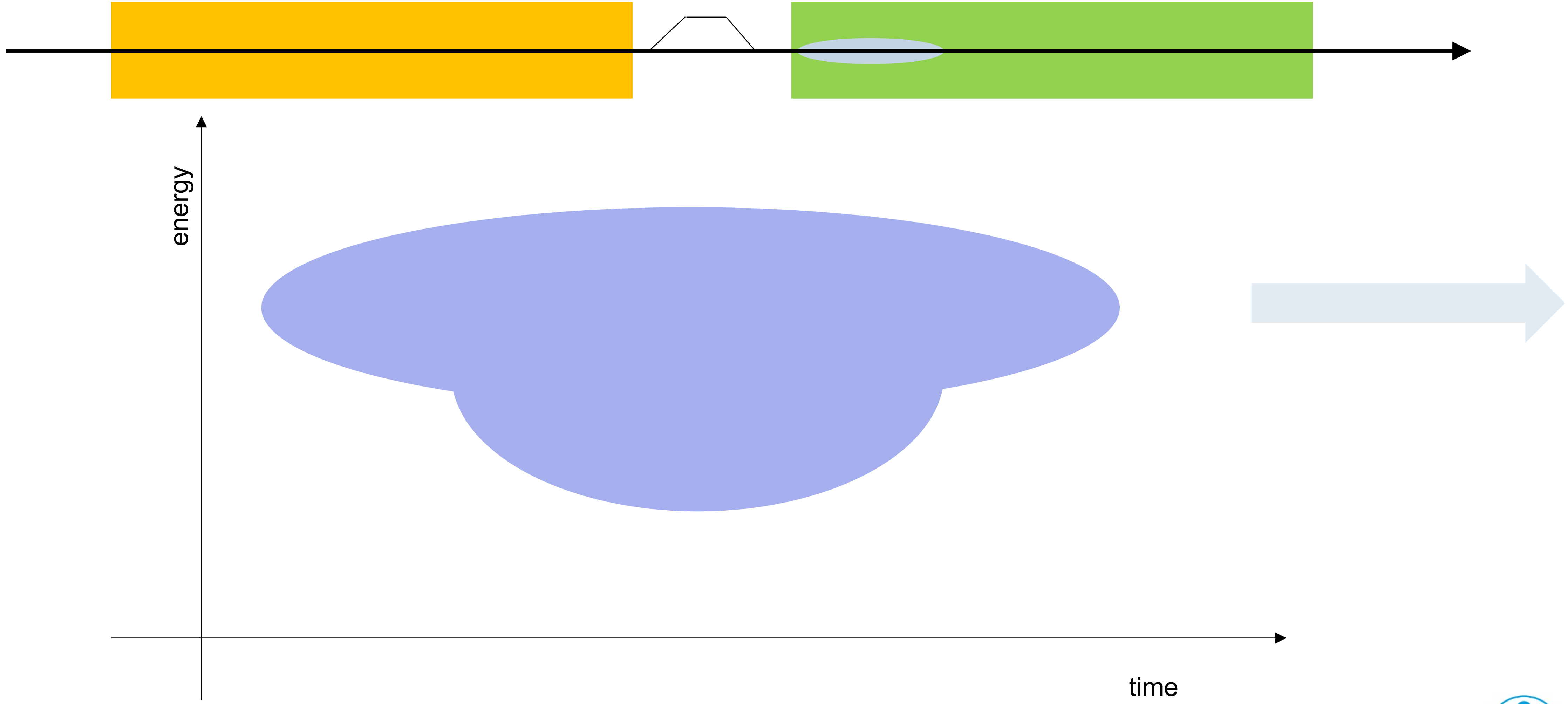
Example: Two-colour FEL

- Full lasing in first colour



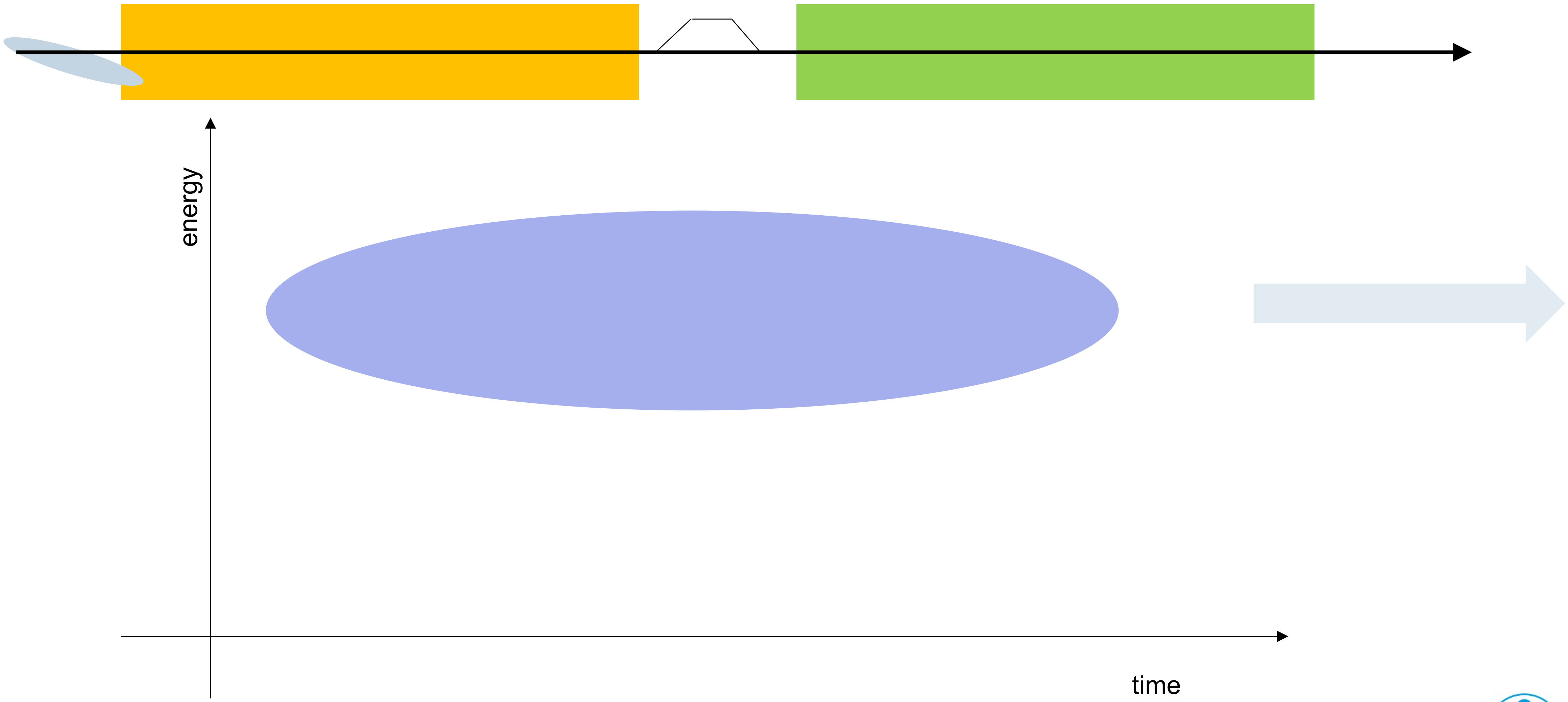
Example: Two-colour FEL

- Lasing in second colour is suppressed due to large energy spread generated from first colour



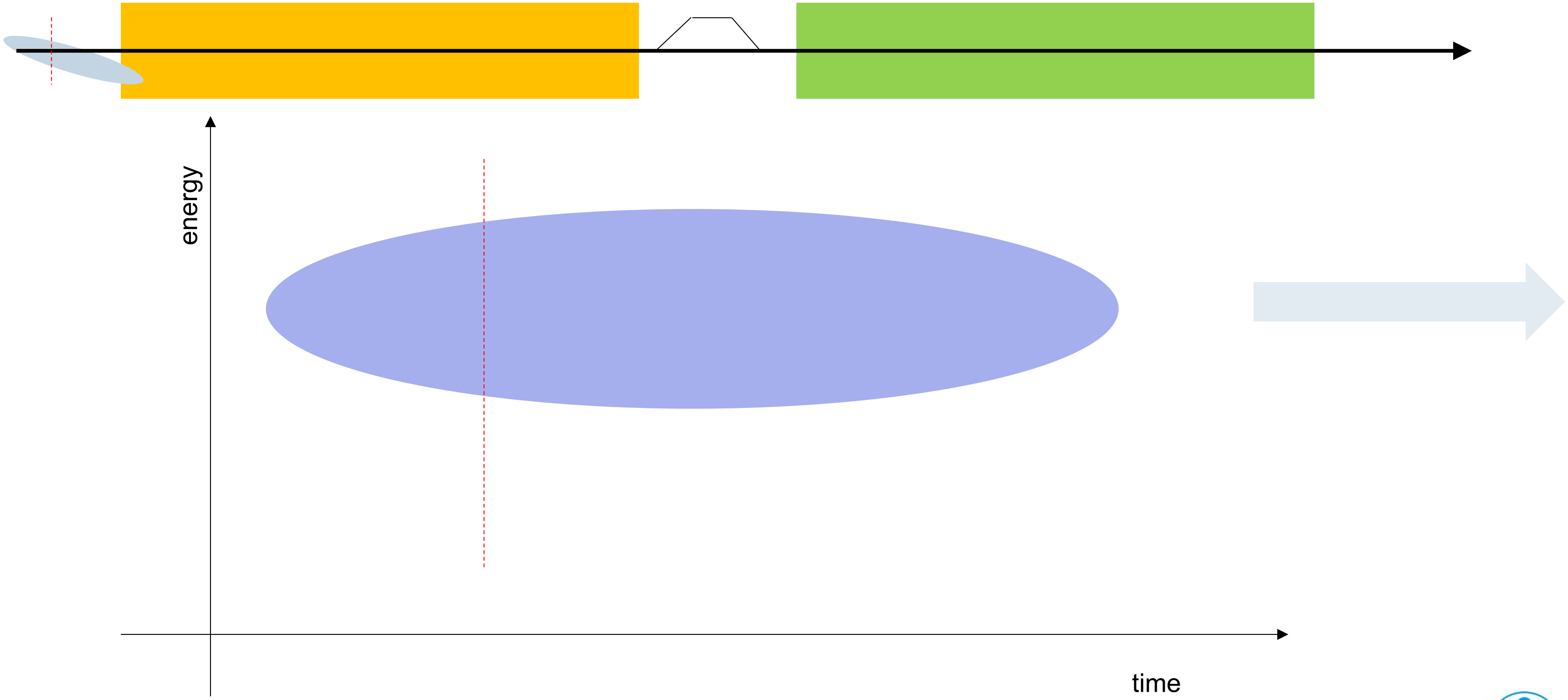
Example: Two-colour fresh slice

- Beam can be tilted to spurs the first colour except for the centred slices



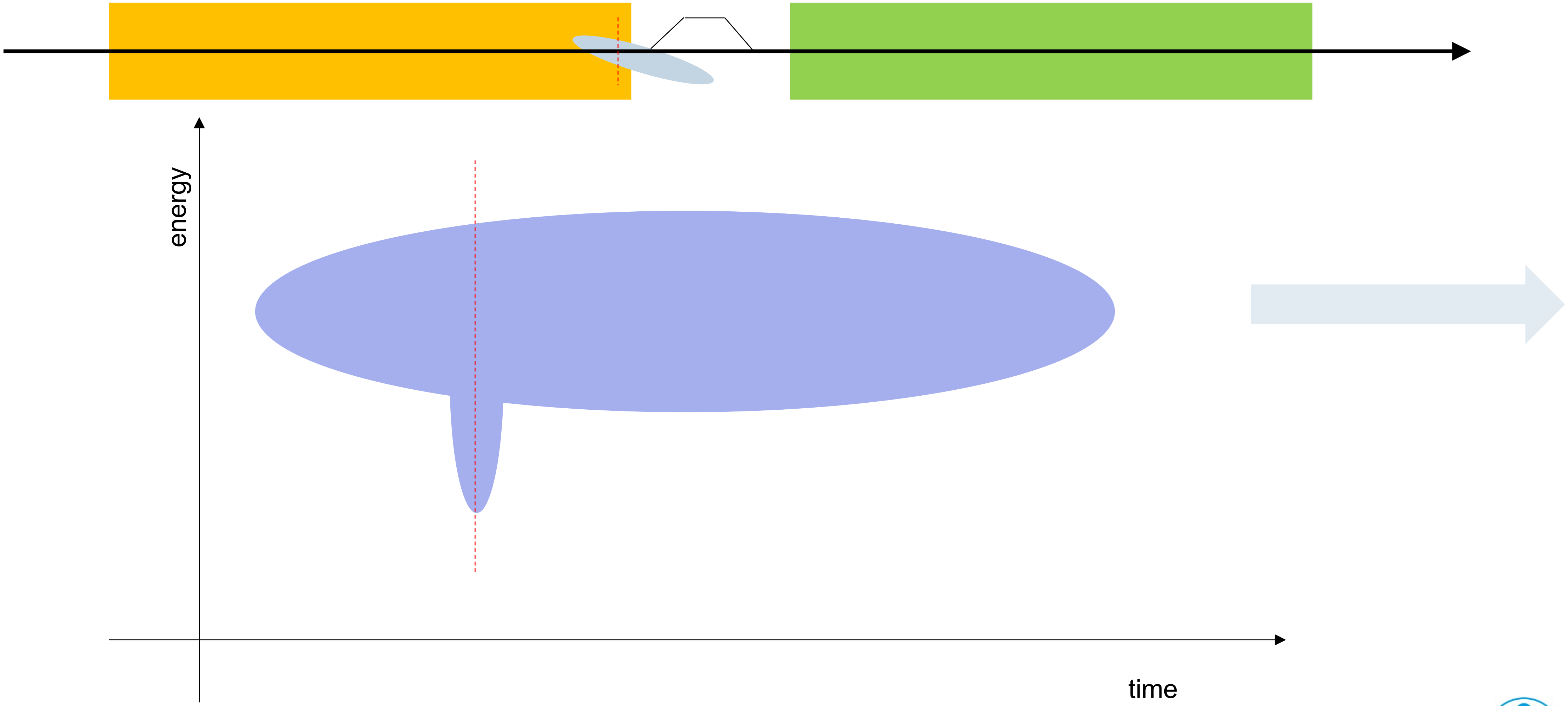
Example: Two-colour fresh slice

- Beam can be tilted to spurs the first colour except for the centred slices



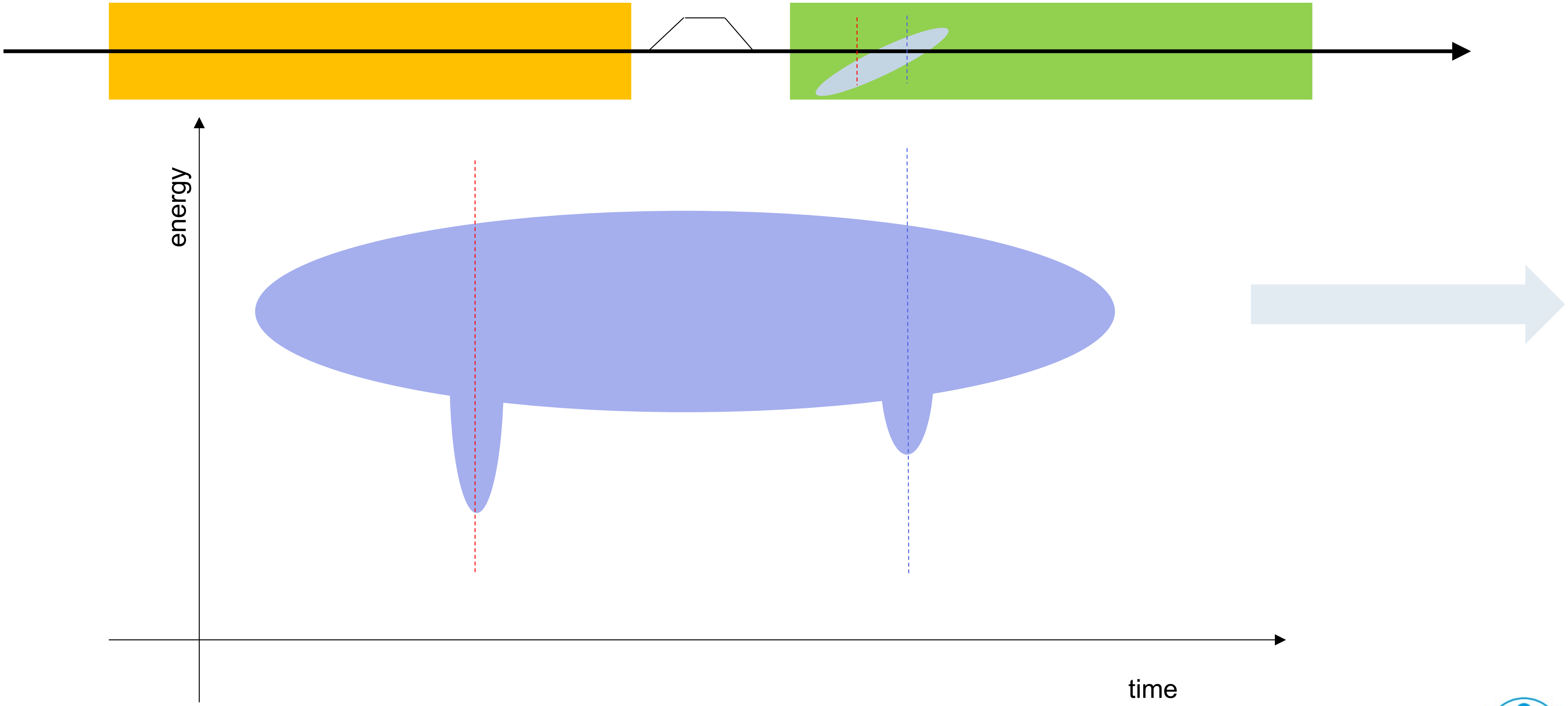
Example: Two-colour fresh slice

- Beam can be tilted to spurs the first colour except for the centred slices

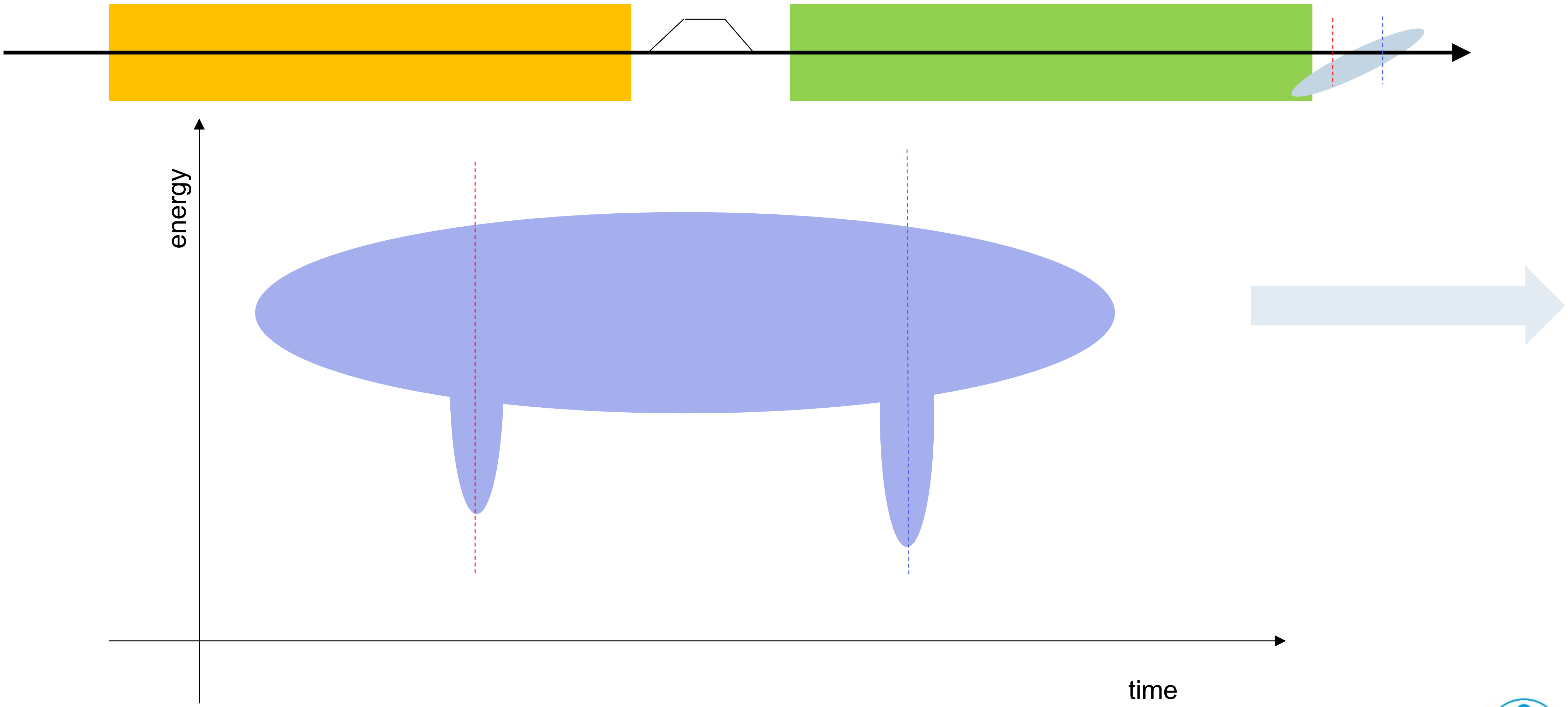


Example: Two-colour fresh slice

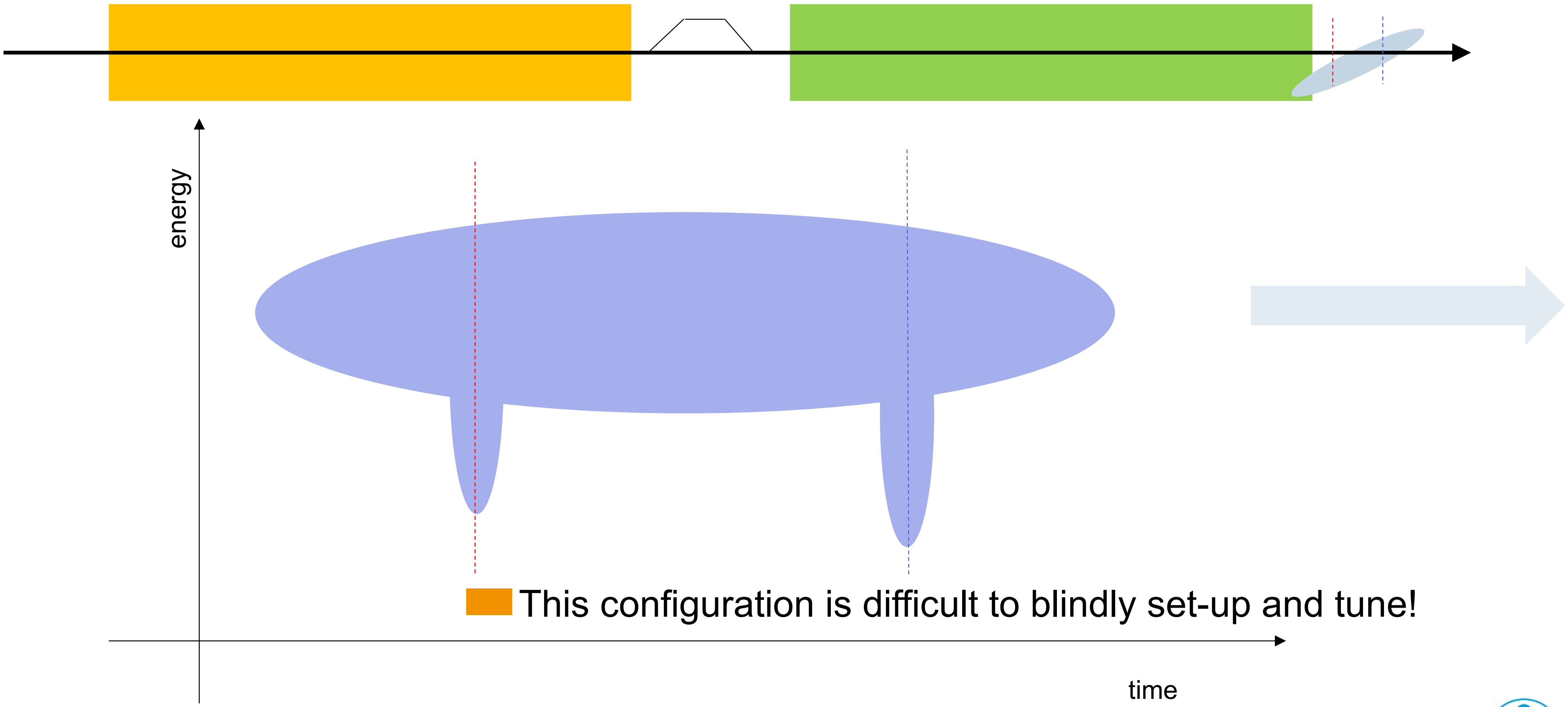
- Tilt can be shifted for the second colour to radiate on a fresh slice



Example: Two-colour fresh slice



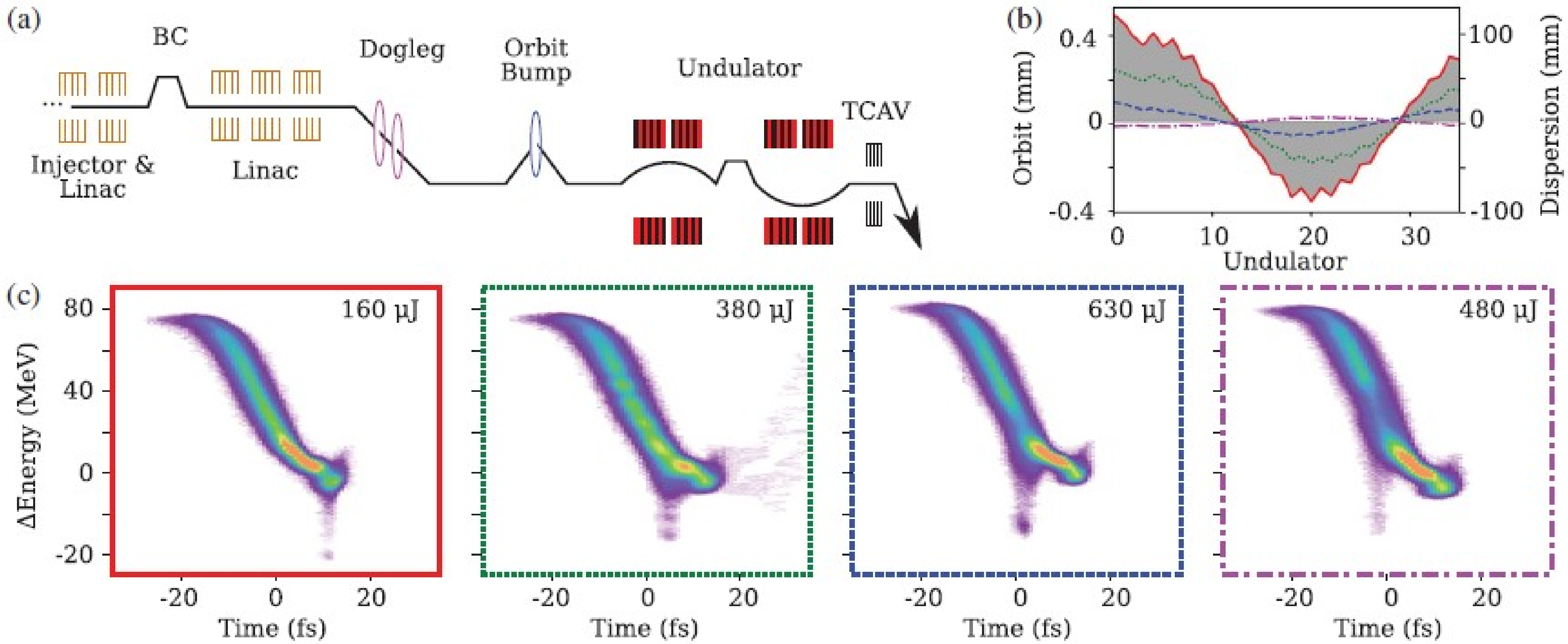
Example: Two-colour fresh slice



- This configuration is difficult to blindly set-up and tune!

Measurement of longitudinal phase-space after fresh-slice lasing

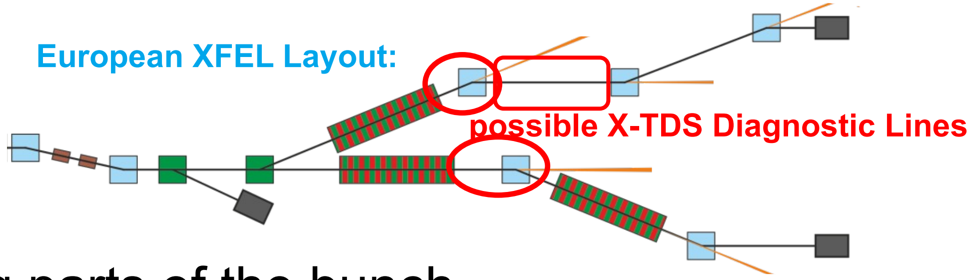
Example: Fresh-Slice Guetg et al. Phys. Rev. Lett.120, 264802 (2018)



Introduction

- Project Goals
  - X-band TDS system downstream of undulator line
  - ~1fs longitudinal resolution
  - sufficient energy resolution (~1MeV) to observe lasing parts of the bunch
  - Semi-parasitic operation possible for multi bunch operation

European XFEL Layout:

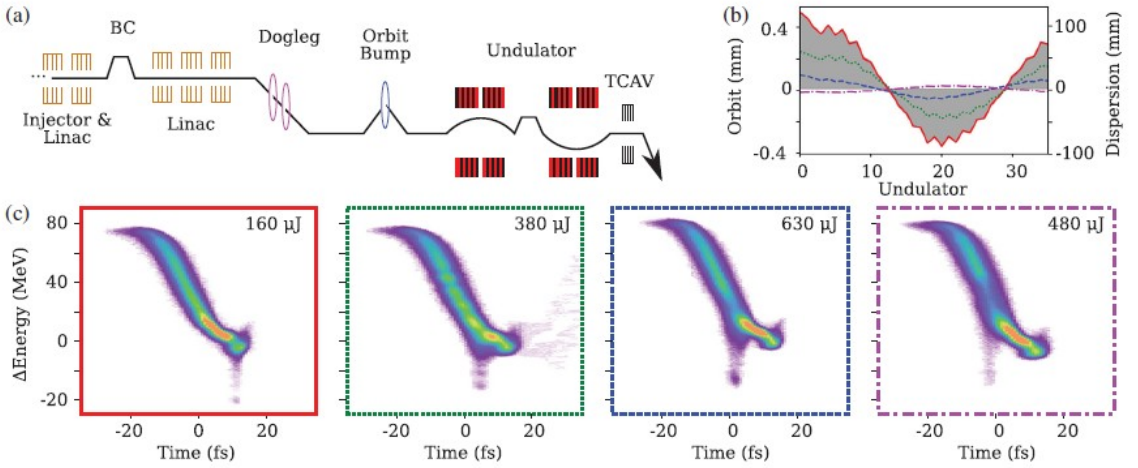


- Very helpful in SASE setup and tuning (e.g. LCSL operational experience) and essential for advanced lasing schemes.

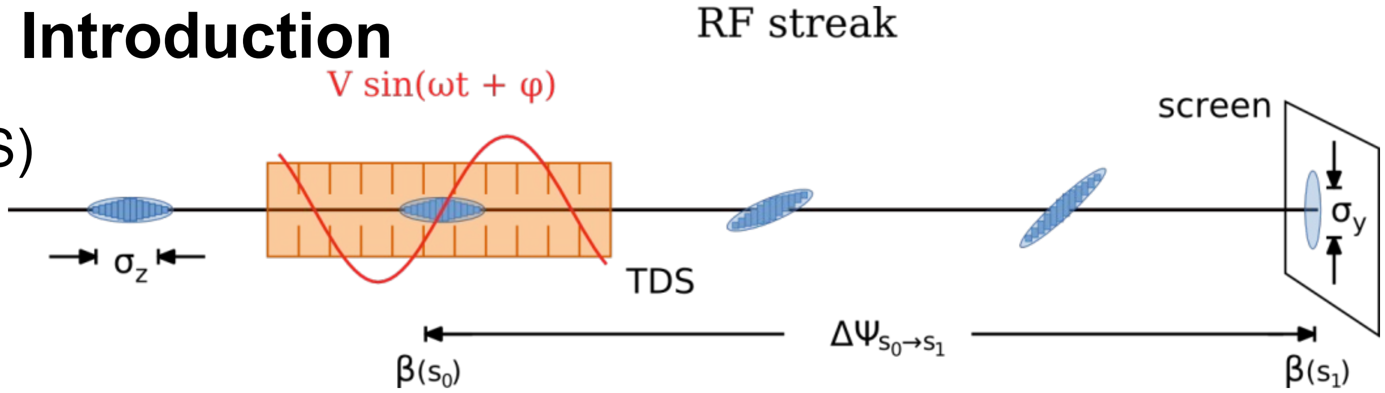
- Similar to wakefield diagnostic "dechirper" but more versatile and less limited in operation however with much increased complexity.

- In addition accurate estimates of the photon pulse duration can be delivered to user stations.

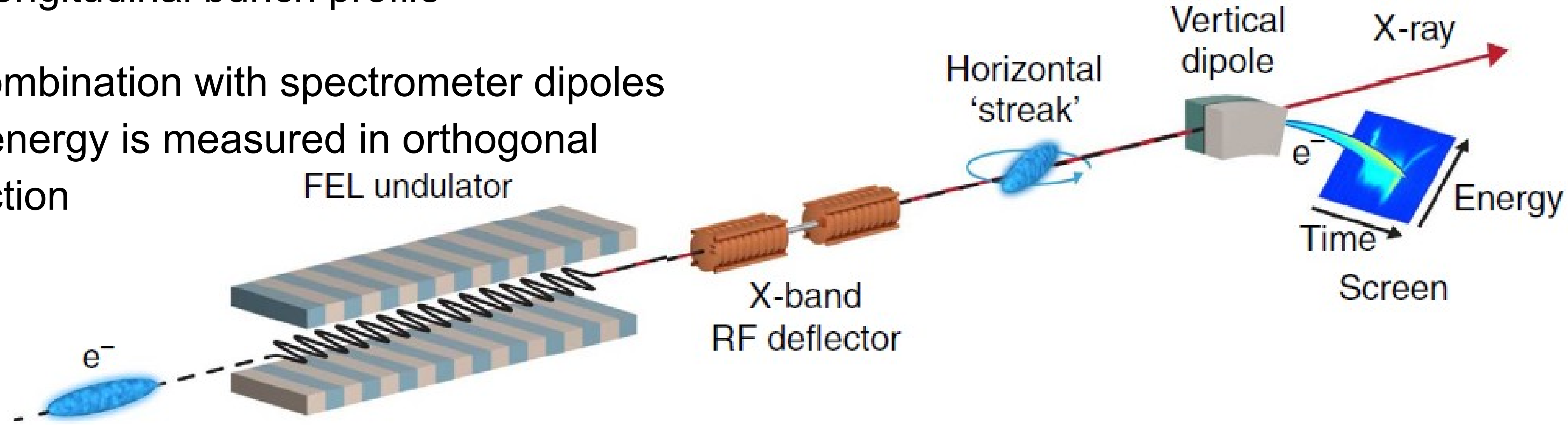
Example: Fresh-Slice Guetg et al. Phys. Rev. Lett.120, 264802 (2018)



Transverse Deflecting Structure Introduction

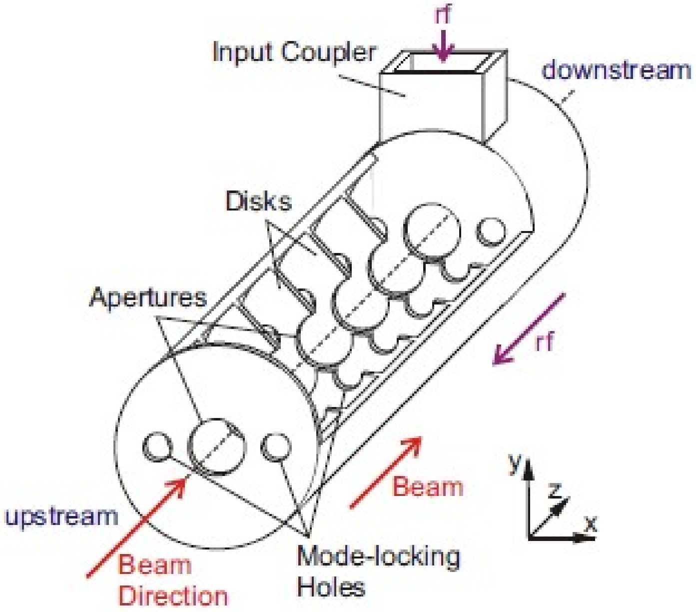


- A transverse deflecting structure (TDS) induces a kick correlated with longitudinal position along the bunch
- The resulting streaked spot size is correlated with the longitudinal bunch profile
- In combination with spectrometer dipoles the energy is measured in orthogonal direction



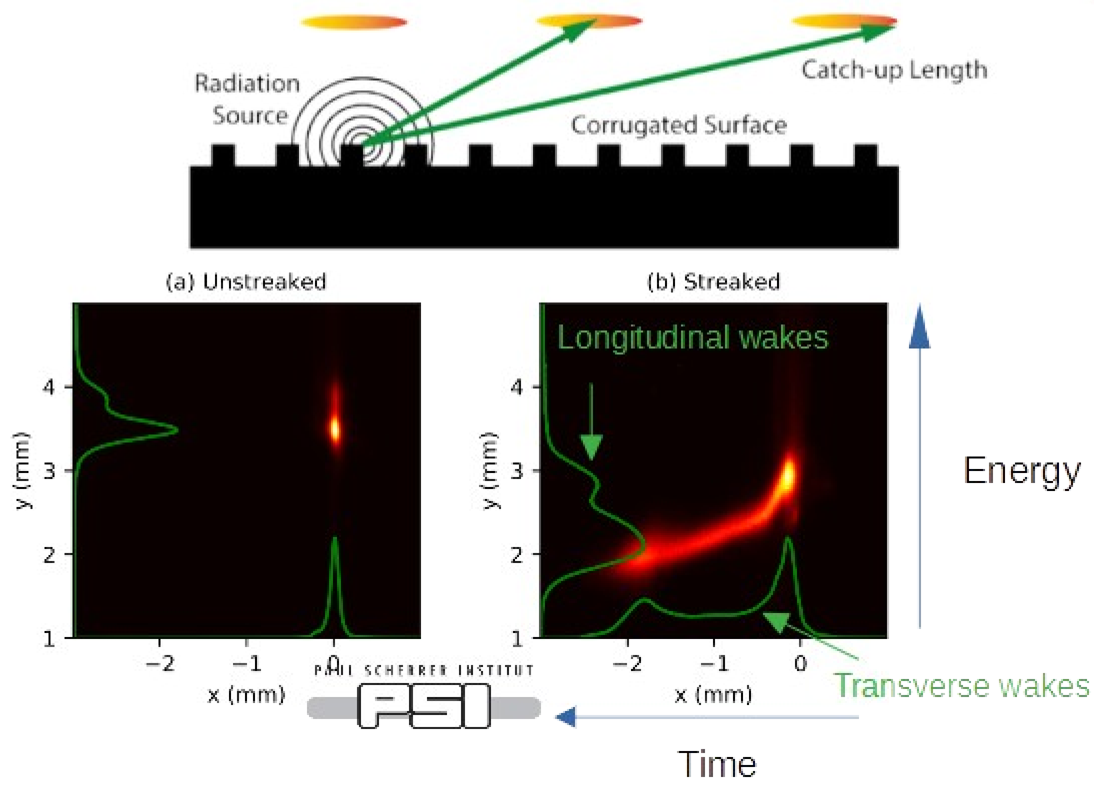
- Downstream of an FEL undulator such a setup can be used to identify lasing parts of the beam

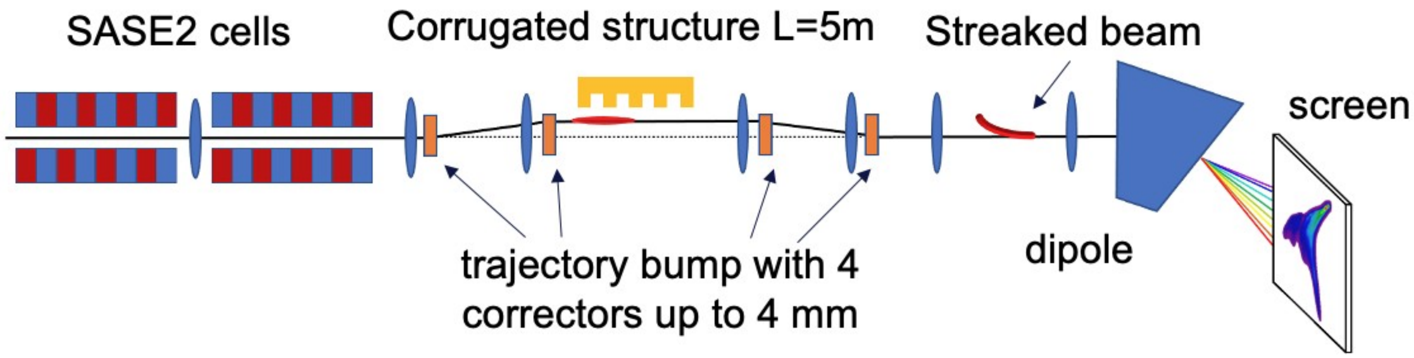
Transverse Deflecting Structure (TDS)



- At XFEL S-band deflectors are used in the injector and B2, as well as LOLA at FLASH
- S-band (3GHz) is not sufficient for femtosecond resolution therefore X-band (12GHz) is used after the undulators
- Difficulty due to much higher beam energy than FLASH

Passive Streaker ("Dechirper")





- A passive streaker an be used to study the longitudinal phase-space
- A corrugate structure close to the beam creates transverse wake fields which streakes the beam
- Analysis is complicated – the wake depends on the longitudinal profile which is what I want to measure
- Streaking field is naturally synchronised with the beam

Slide from Dijkstal, Tomin, Wohlenberg

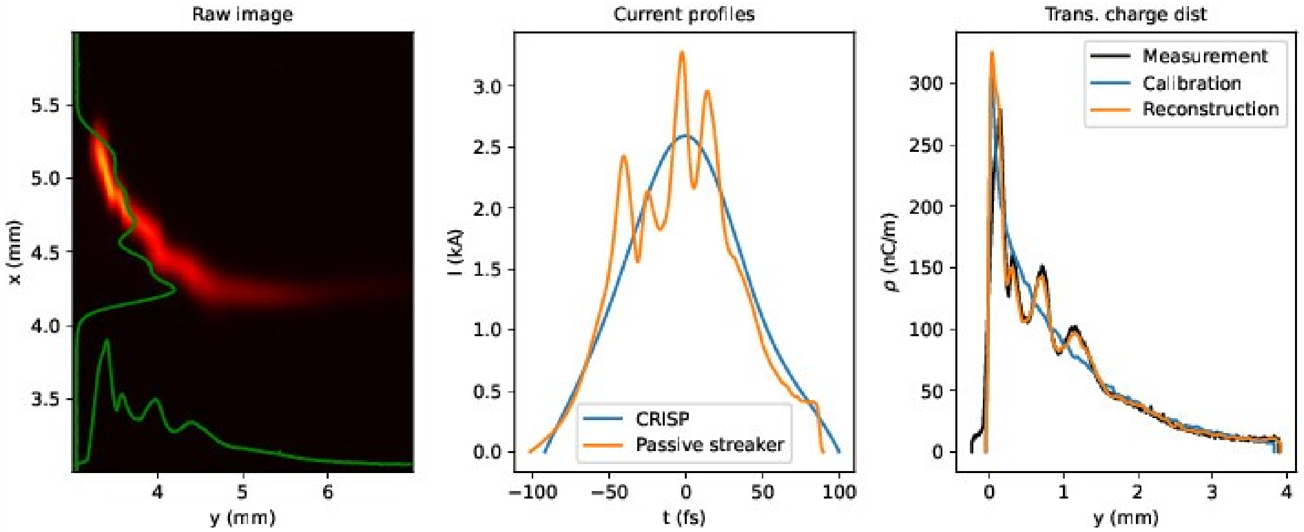
First Successful Operation of “Dechirper” XFEL

Logbook entry: /XFELelog/data/2022/36/07.09_a

07.09.2022 20:14 **not set** Dijkstal **First passive streaker measurements**

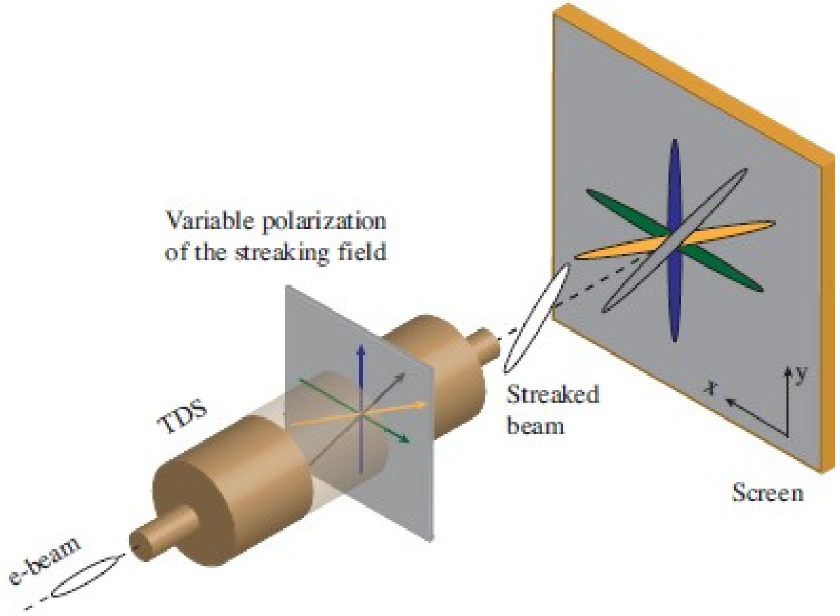
```
I used the CRISP measurement to calibrate the distance between beam and structure.
Then I used the reconstruction algorithm to obtain the current profile from a single image.
Probably the CRISP averages over many measurements, therefore it does not resolve the small current
 spikes.

This elogbook entry was sent to following experts:
Guetg Decking
```

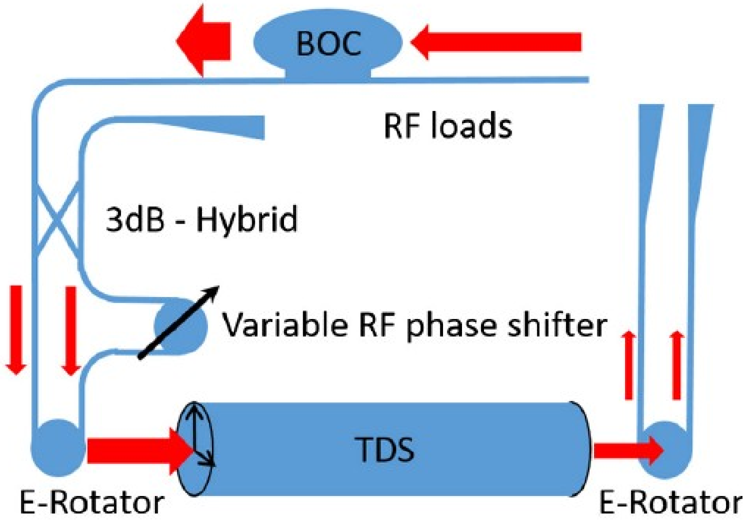
First current profile reconstruction at EXFEL

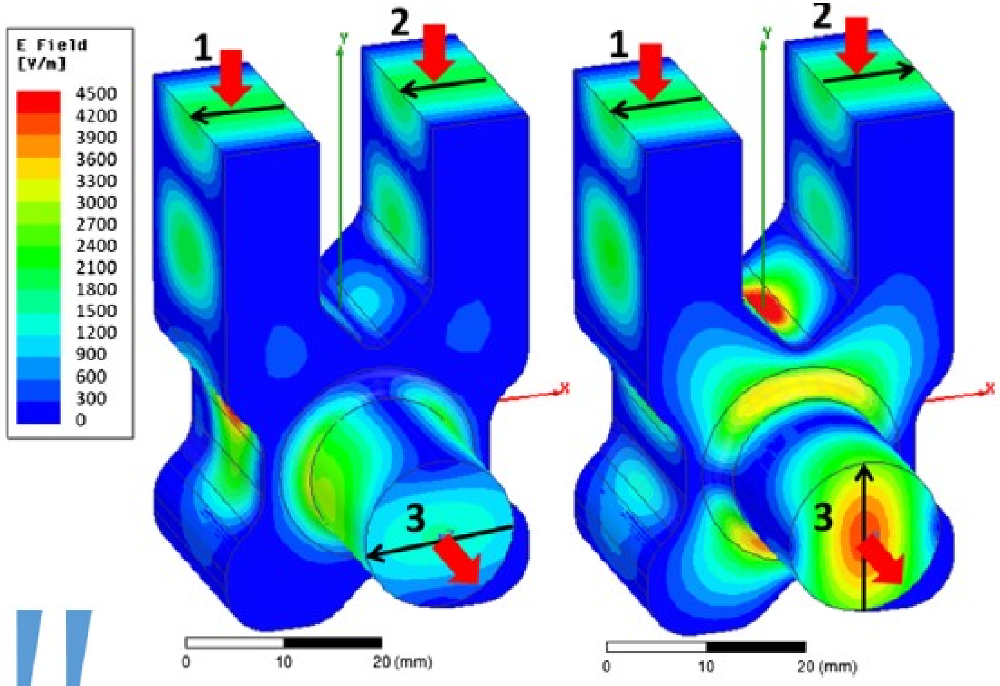


PolariX

- X-Band system (11995 MHz at FLASH) with variable polarisation
- BOC pulse compressor
- Used at FLASH and Ares as well as at SwissFEL
- Collaboration between CERN, PSI and DESY







P. CRAIEVICH et al. PHYS. REV. ACCEL. BEAMS 23, 112001 (2020)

Overview PolariX

Collaboration between PSI, CERN, and DESY

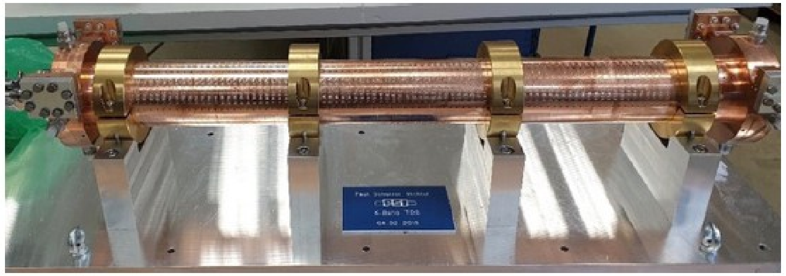


FIG. 22. Full TDS prototype.

TABLE I. Beam parameters, spatial constraints and specifications for the PolariX TDS design for the experiments at DESY and PSI.

	Unit	SINBAD	FLASH2	FLASHForward	ATHOS
Charge	pC	0.5–30	20–1000	20–500 (driver) 10–250 (witness)	10–200
Normalized rms emittance	μm	0.1–1	0.4–3	2.0–5.0 (driver) 0.1–1.0 (witness)	0.1–0.3
rms bunch length	fs	0.2–10	$< 3 - 200$	50–500 (driver) 1–10 (witness)	<1
β-function at the TDS	m	10–50	7–20	50–200	50
Beam Energy	MeV	80–200	400–1350	500–2500	2900–3400
Repetition rate	Hz	10–50	10	10	100
TDS integrated voltage	MV	25–40	30–40	25–30	30–60
Number TDS		2	2	1	2
Maximum length	m	3	< 1.92	< 2	4
TDS iris	mm	4	4	4	4
TDS frequency	MHz	11991.6	11988.8	11988.8	11995.2
Operational temperature	°C	48	62	62	25–35

P. CRAIEVICH et al. PHYS. REV. ACCEL. BEAMS 23, 112001 (2020)

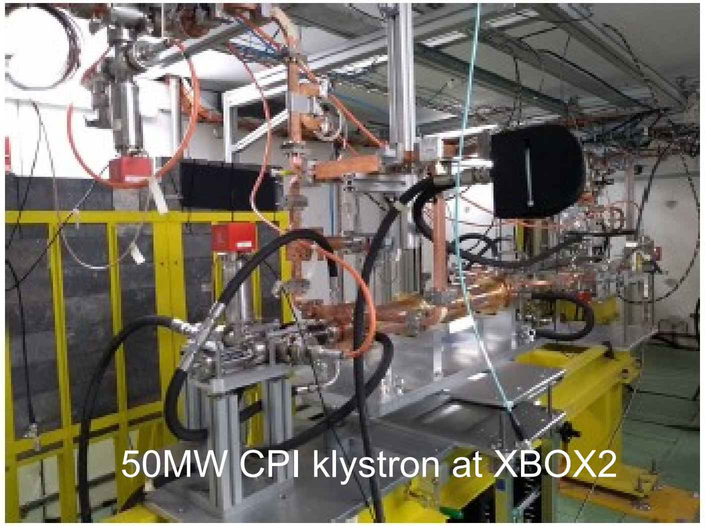
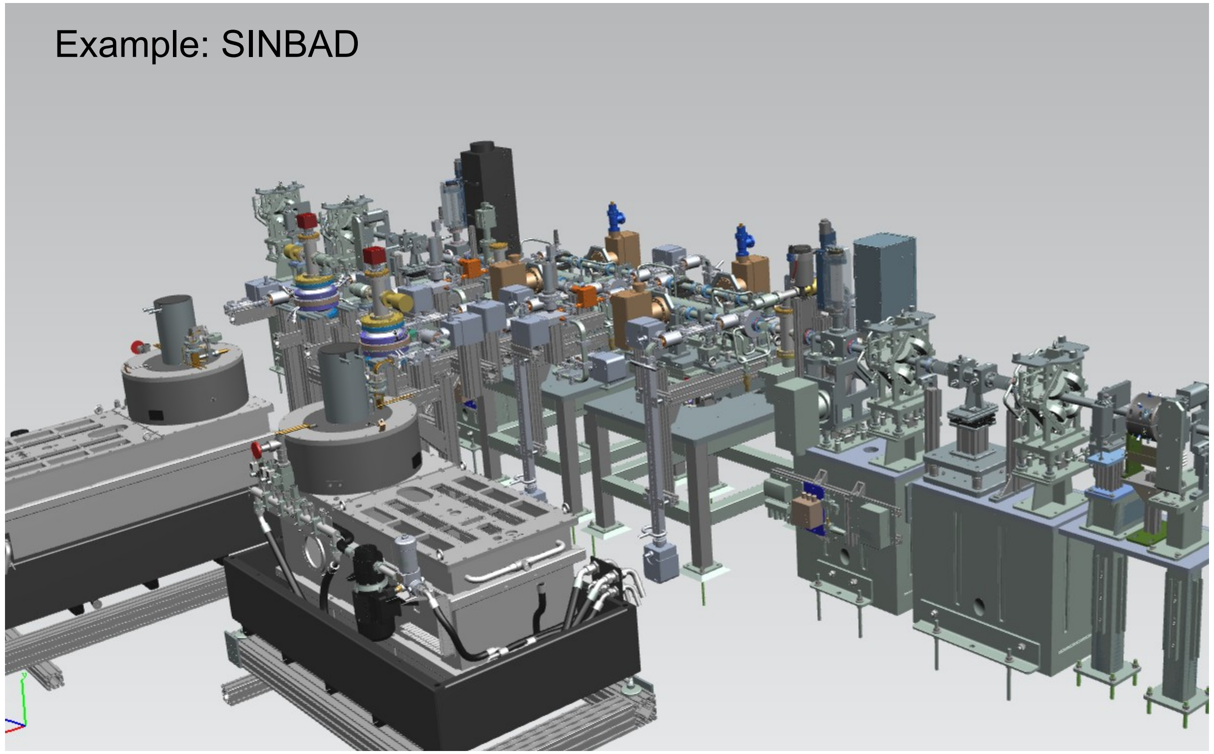


FIG. 29. The PolariX TDS installed in the XBOX2 test stand.



Overview PolariX

Collaboration between PSI, CERN, and DESY

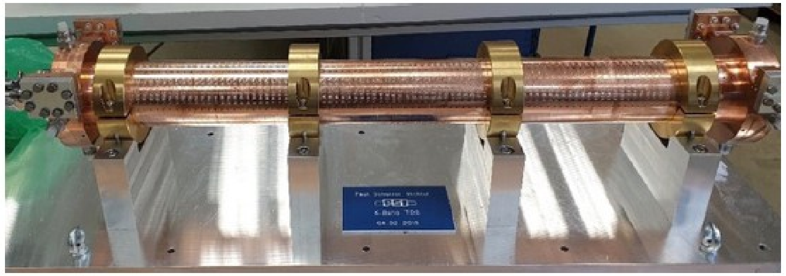


FIG. 22. Full TDS prototype.

We would need about 80MV

TABLE I. Beam parameters, spatial constraints and specifications for the PolariX TDS design for the experiments at DESY and PSI.

	Unit	SINBAD	FLASH2	FLASHForward	ATHOS
Charge	pC	0.5–30	20–1000	20–500 (driver) 10–250 (witness)	10–200
Normalized rms emittance	μm	0.1–1	0.4–3	2.0–5.0 (driver) 0.1–1.0 (witness)	0.1–0.3
rms bunch length	fs	0.2–10	$< 3 - 200$	50–500 (driver) 1–10 (witness)	<1
β-function at the TDS	m	10–50	7–20	50–200	50
Beam Energy	MeV	80–200	400–1350	500–2500	2900–3400
Repetition rate	Hz	10–50	10	10	100
TDS integrated voltage	MV	25–40	30–40	25–30	30–60
Number TDS		2	2	1	2
Maximum length	m	3	< 1.92	< 2	4
TDS iris	mm	4	4	4	4
TDS frequency	MHz	11991.6	11988.8	11988.8	11995.2
Operational temperature	°C	48	62	62	25–35

P. CRAIEVICH et al. PHYS. REV. ACCEL. BEAMS 23, 112001 (2020)

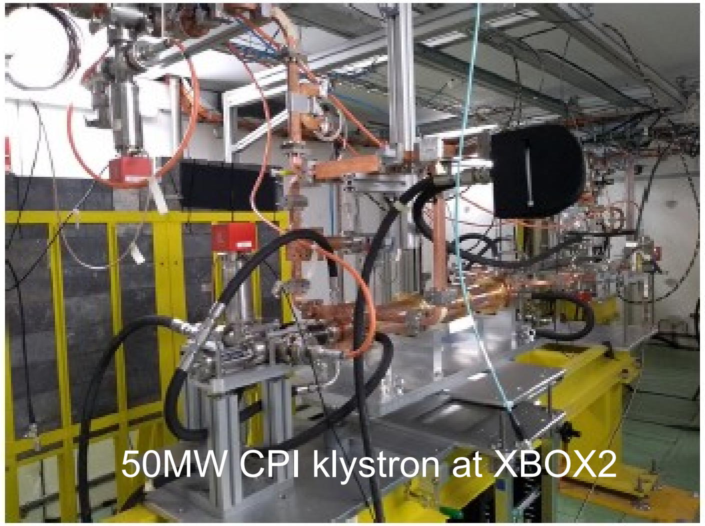
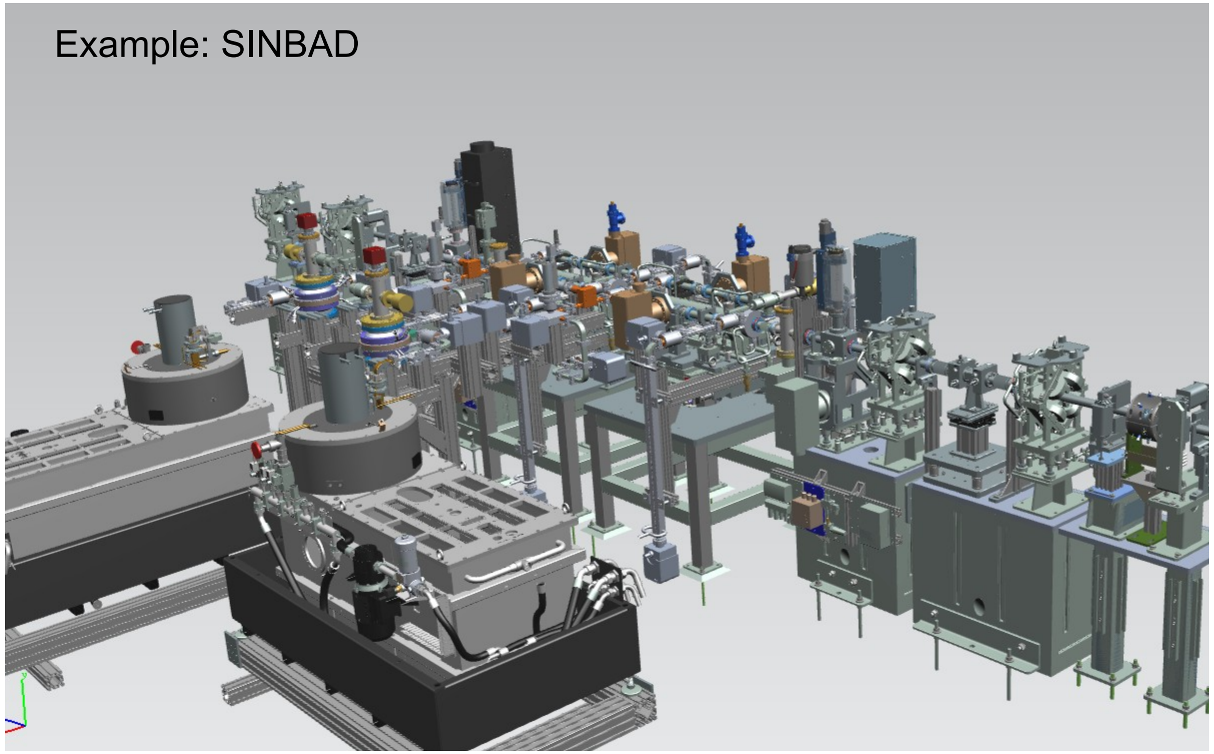
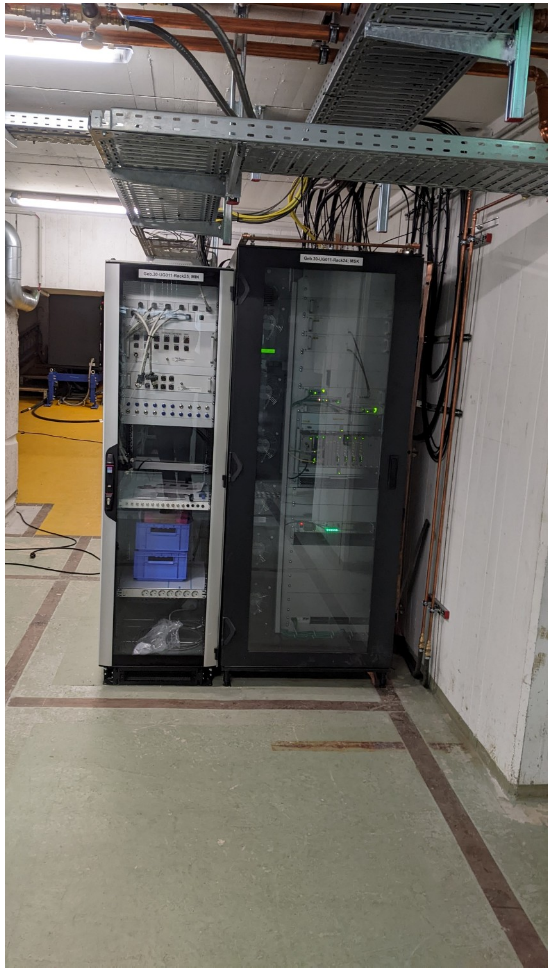
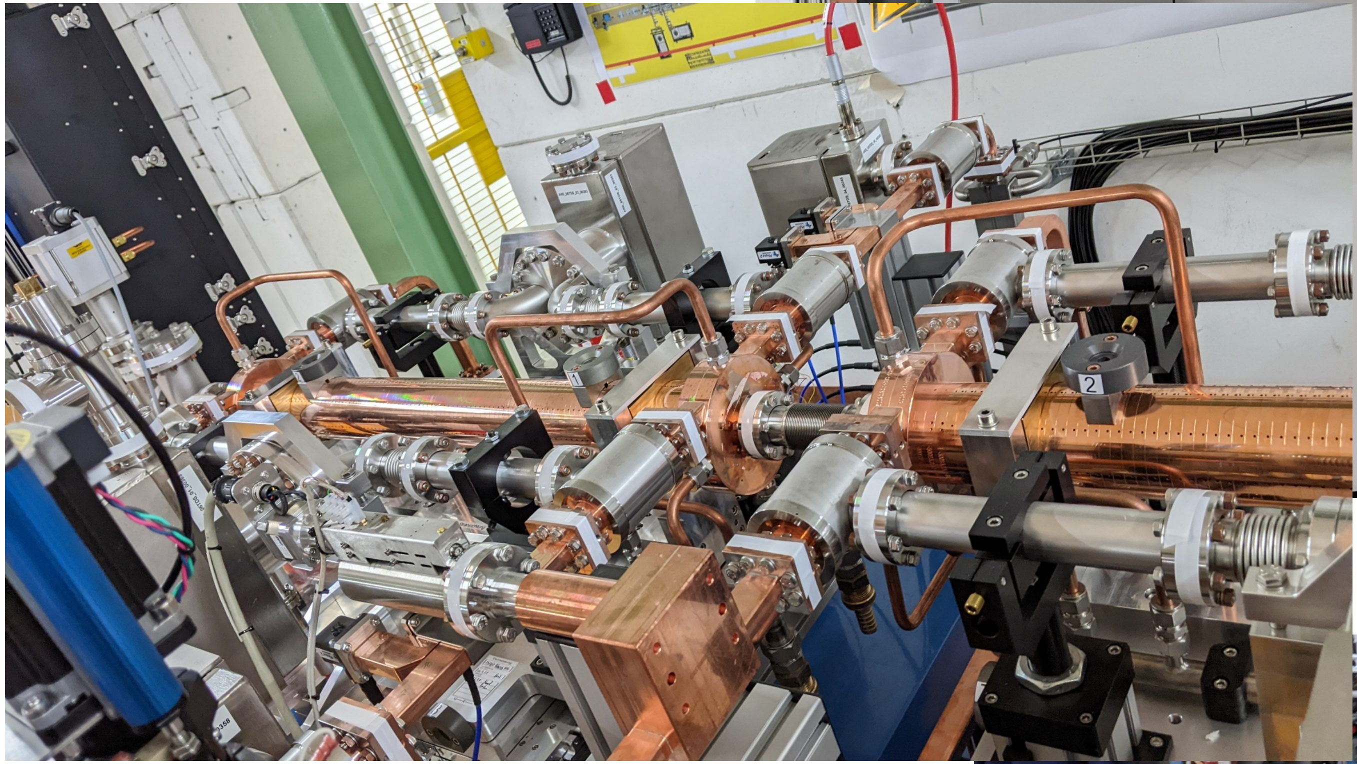


FIG. 29. The PolariX TDS installed in the XBOX2 test stand.

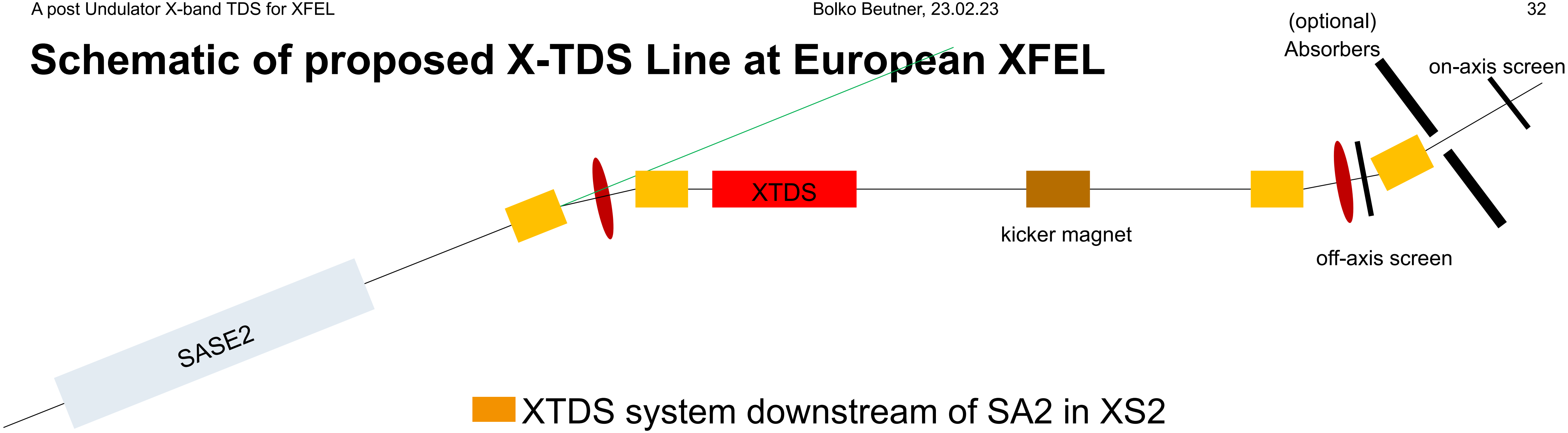


Installation at ARES



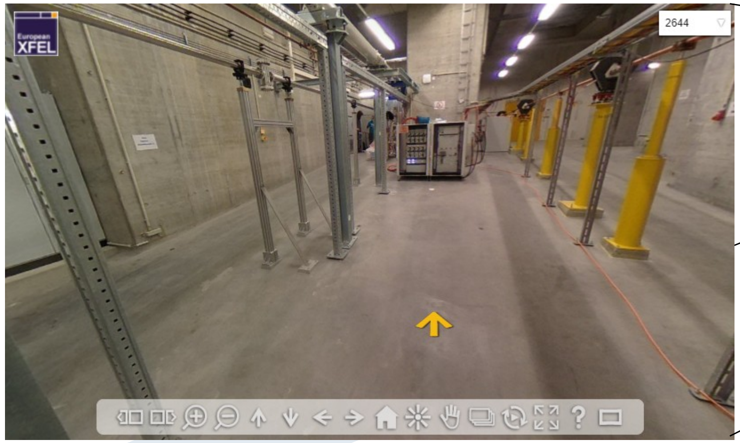


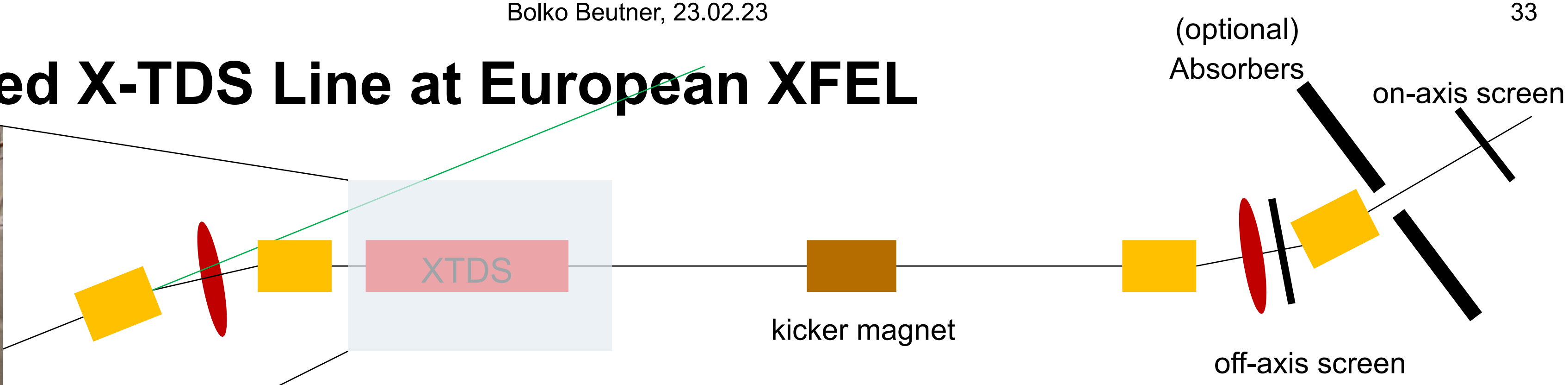
Schematic of proposed X-TDS Line at European XFEL

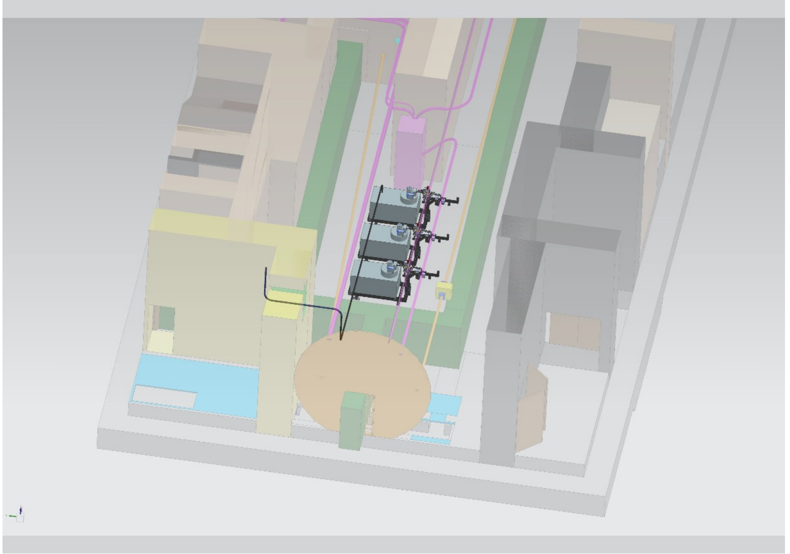


- XTDS system downstream of SA2 in XS2
- Space for 3 RF stations similar to FLASH 1
- off-axis screen in dispersive section in downstream transport
- Earliest possible installation 2025 but no decision yet

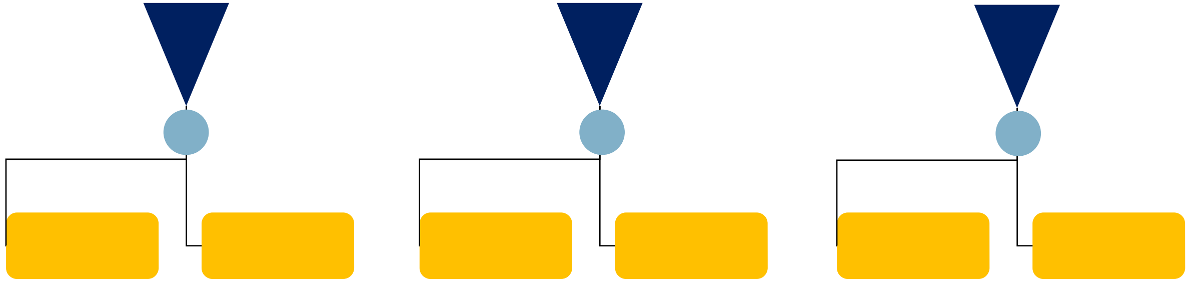
Schematic of proposed X-TDS Line at European XFEL



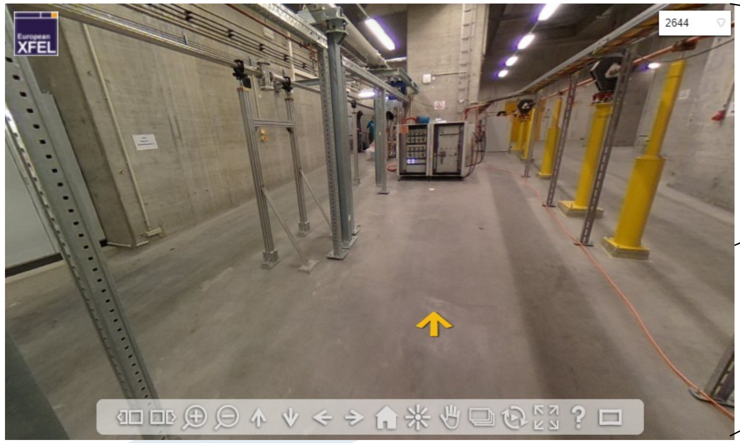


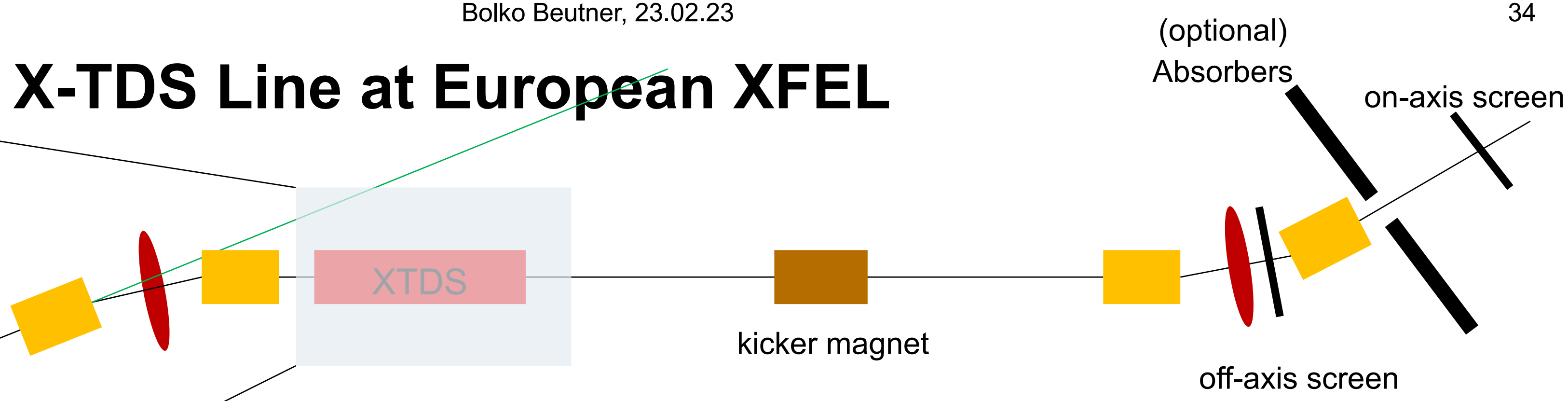


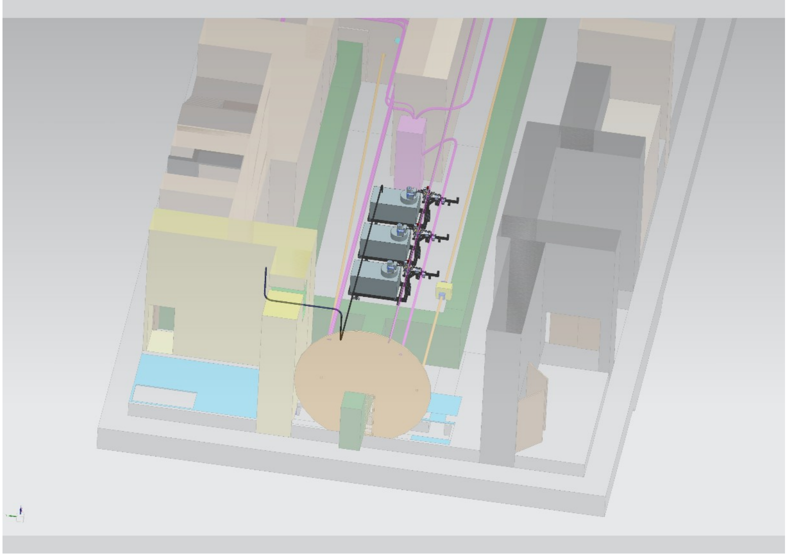
- XTDS system downstream of SA2 in XS2
- Space for 3 RF stations similar to FLASH 1
- off-axis screen in dispersive section in downstream transport
- Installation not before 2025 but no decision yet



Schematic of proposed X-TDS Line at European XFEL







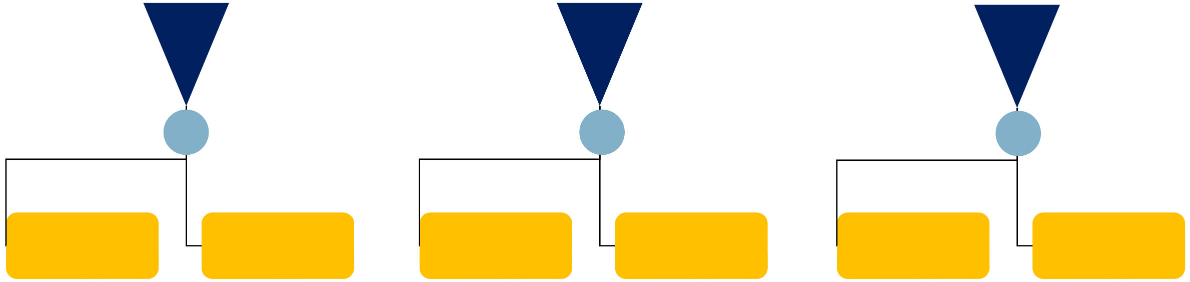
- Analytic estimates:

6MW	voltage	14GeV	17.5GeV
3x double 1m	78.4MV	1.01fs	1.13fs
7.5MW	**voltage**	**14GeV**	**17.5GeV**
3x double 1m	87.7MV	0.90fs	1.01fs

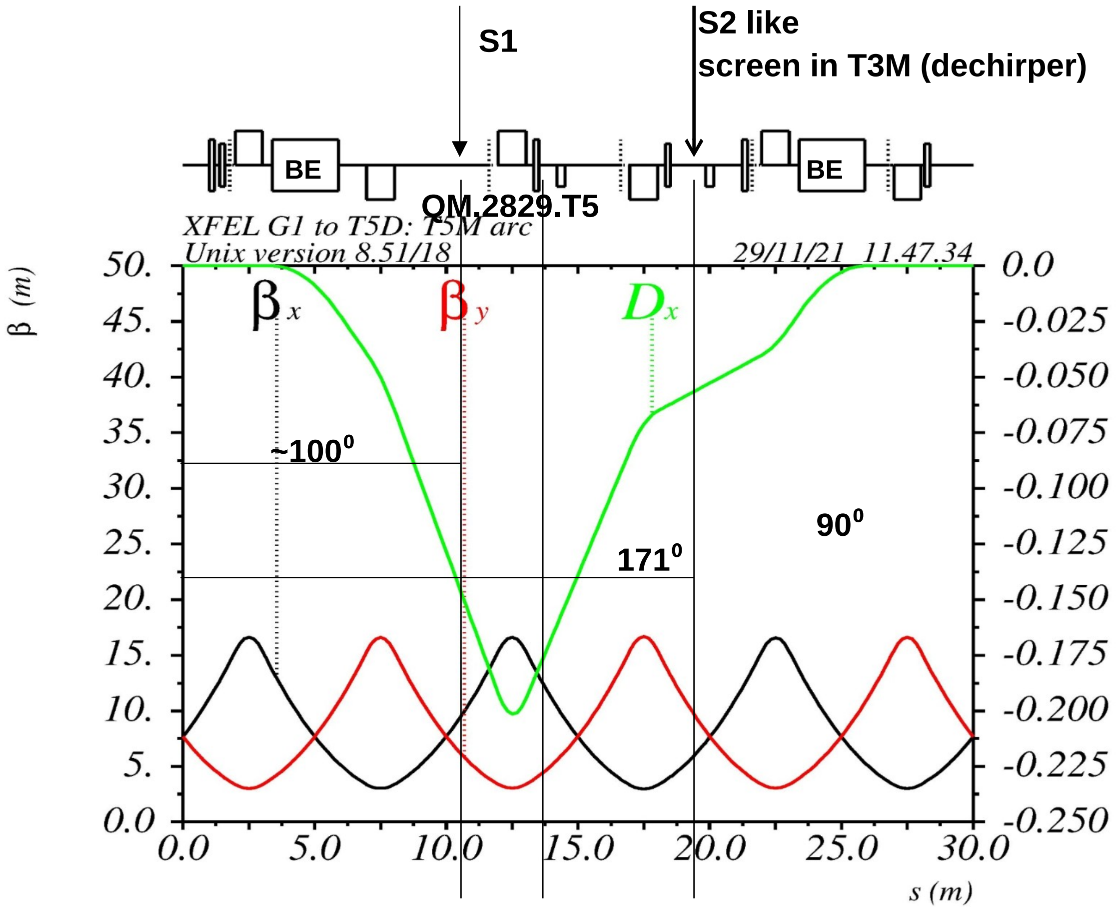
15% losses

100m beta at TDS
0.5mm mrad

- RF design is work in progress



Beam optics for Screen Stations

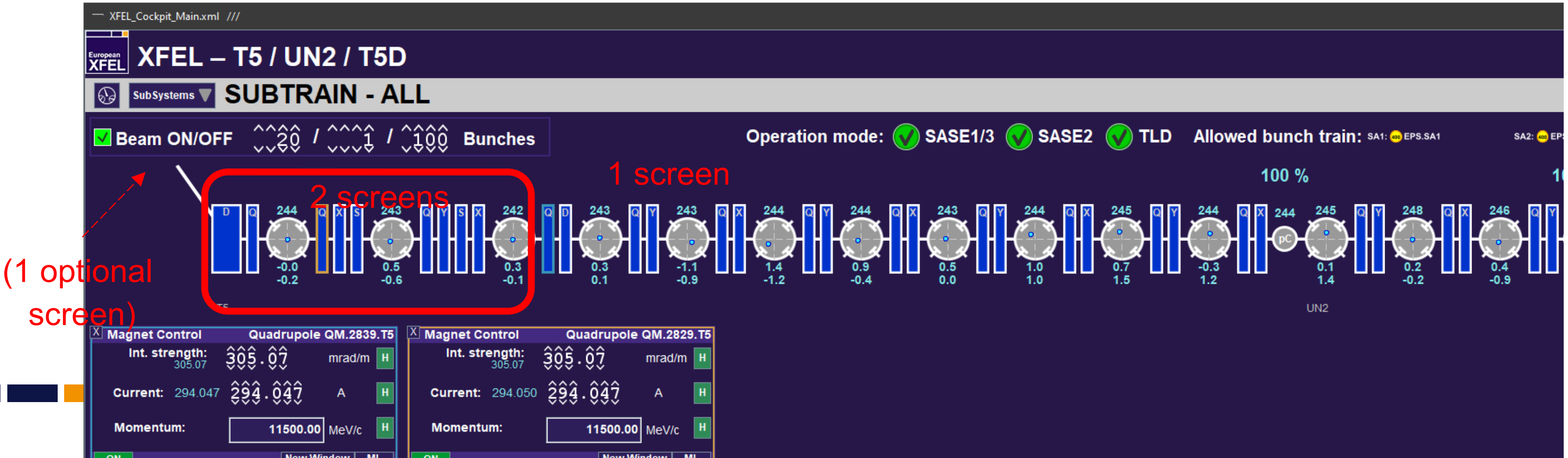


TDS		
β_y	55.526	
μ_y	1.931	(measured from T3_start)
Screen	S1	S2
β_y	5.069	11.787
μ_y	2.799	3.002
σ_y	13.6 μm	19.5 μm
TDS – Screen		
R34	-12.37	+11.04
Δμ_y	312^0	385^0
Screen Screen		
β_x	11.184	4.707
σ_x	20.2 μm	13.1 μm
|D_x|	0.161	0.060
σ_x/D_x	12.5e-5	21.8e-5

Screen Stations

- We would need 3 screen stations at:
  - position similar to the dechirper screen (S2 from previous slide)
  - At a higher dispersion position (S1) which might collide with a future photon chamber
  - downstream of the bend dipoles – for slice emittance without dispersion or a high resolution single bunch optics

  - Possibly a station upstream of the bend but space requirements of other projects (or required screen stations) have to be taken into account.



Summary and Outlook

- A X-TDS system would be more versatile and usable then a “dechiper” but more much complex and expensive
  - RF feasibility Study ongoing
    - XS2 (SASE 2)
    - In photon tunnel (especially SASE 1)
  - Integration of possible future undulator lines (SASE 4 and SASE 5)
  - Challenging space requirements
- 3(4) additional screen stations required with on- and off-axis screens
- Alternative use of an X-TDS as a replacement for the B2 TDS

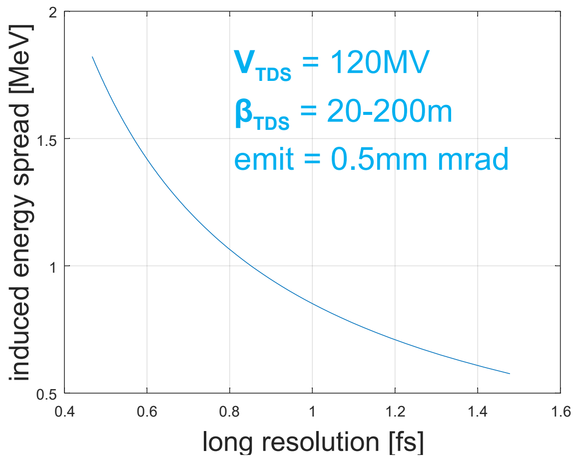
Thank You for Your Attention!

Energy resolution

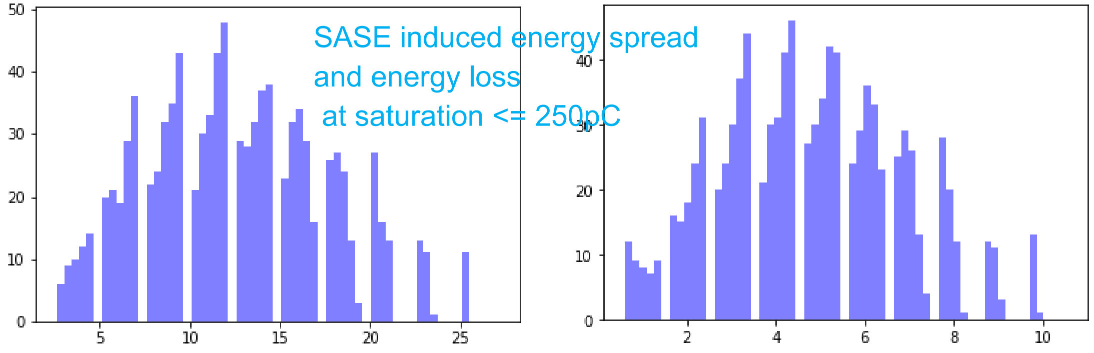
- Energy resolution of the setup is limited by two contributions
  - Intrinsic beam size defined by slice spot size
    - ► about 1 MeV resolution in multi bunch optics
    - ► below 0.5 MeV resolution in single bunch optics
  - Energy spread increase by off-axis longitudinal fields in TDS on the order of 1 MeV

$$\sigma_E = E\frac{\sigma_y}{\eta_y} = E\frac{\sqrt{\beta_{\mathrm{screen}}\varepsilon_n/\beta\gamma}}{\eta}$$

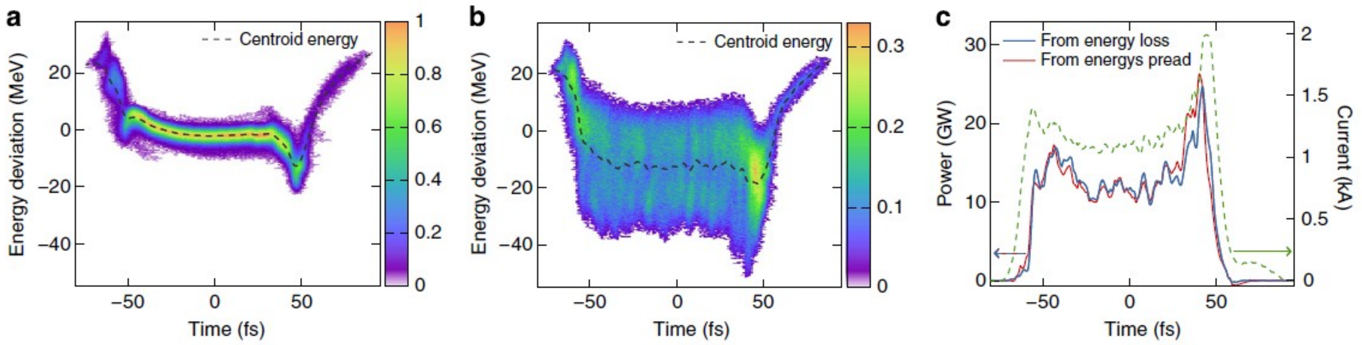
$$\sigma_\delta \cdot \sigma_s \geq \frac{\varepsilon_y}{\sin\Delta\Phi}$$



- Expected energy spread from FEL process is typically well above 2MeV at saturation



E.A. Schneidmiller and M.V. Yurkov, Photon beam properties at the European XFEL Saturation Tables



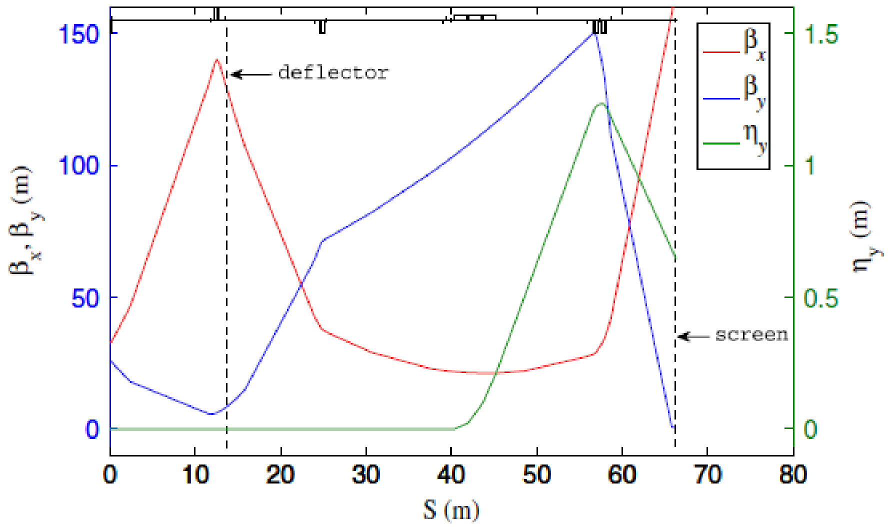
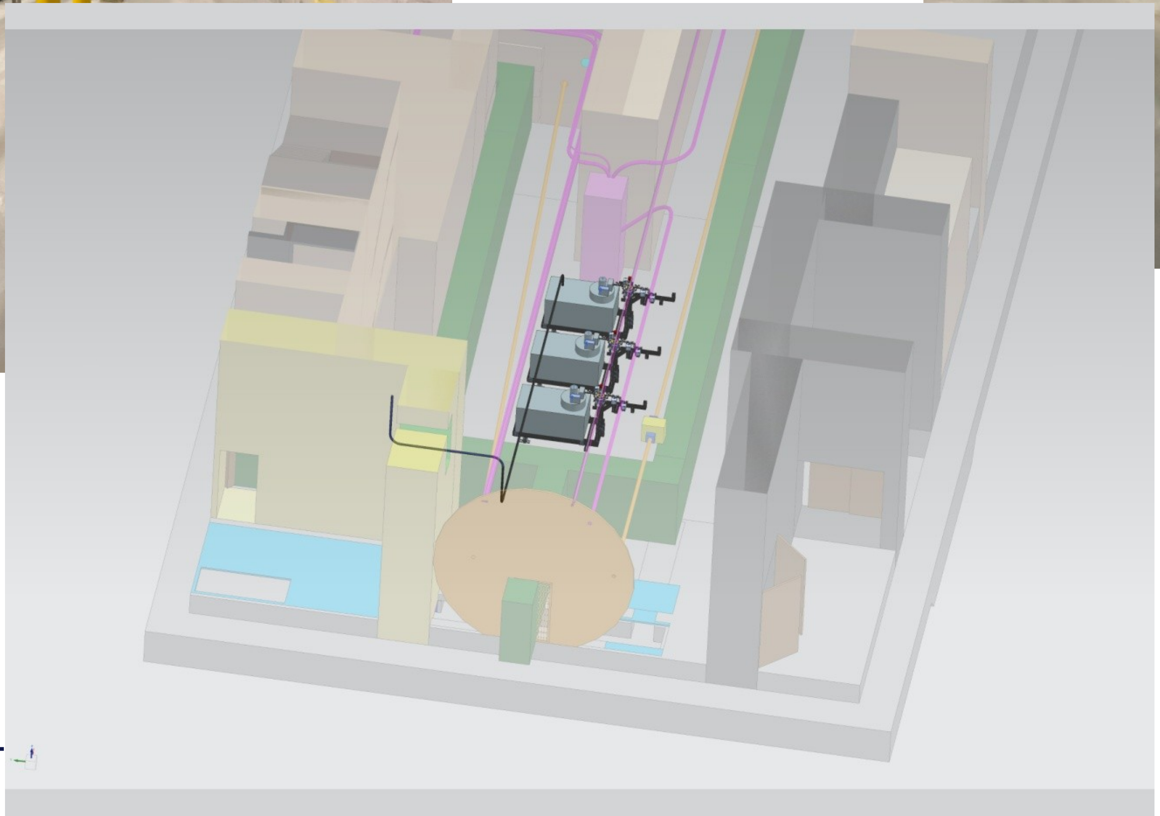


TABLE I. X-band transverse deflector parameters.

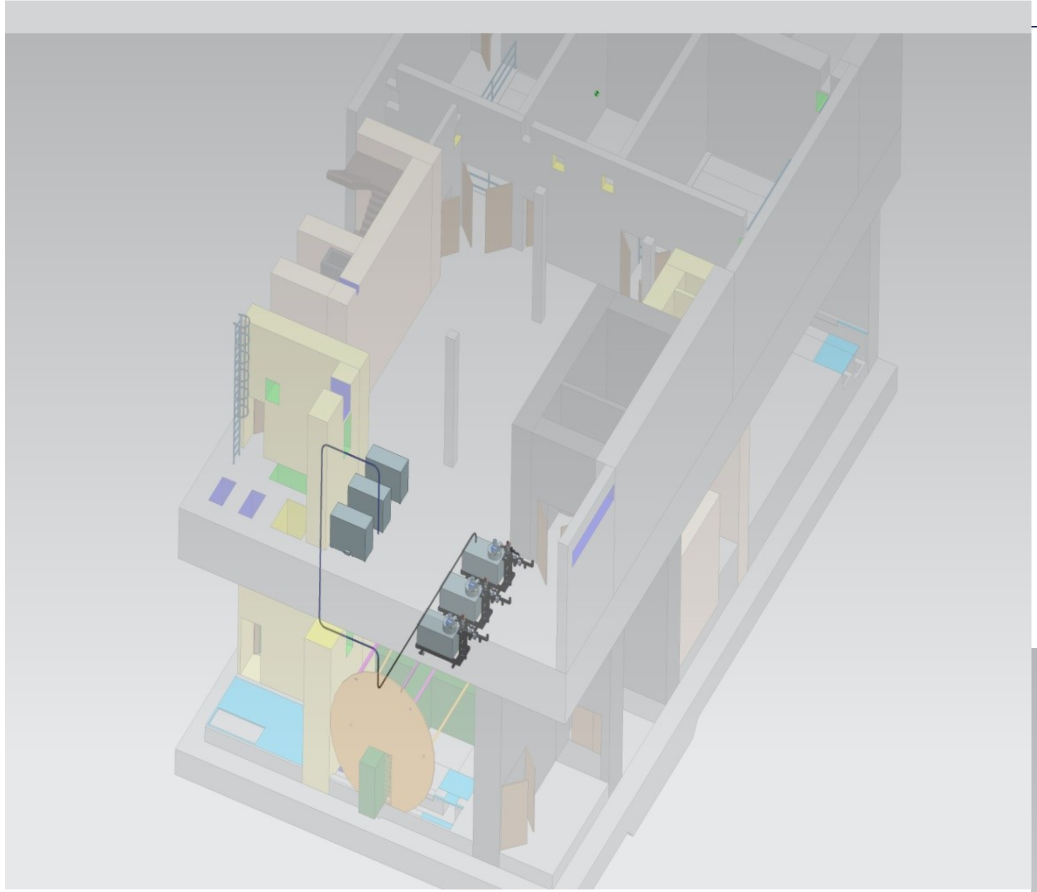
Parameter	Symbol	Value	Unit
rf frequency	f	11.424	GHz
Deflecting structure length	L	2×1	m
rf input power	P	40	MW
Deflecting voltage (on crest)	V_0	48	MV
Soft x-ray (e-beam 4.3 GeV)			
Calibration factor	S	400	
Temporal resolution (rms)	$\sigma_{t,r}$	$\sim$1	fs
Energy resolution (rms)	$\sigma_{E,r}$	56	keV
Hard x-ray (e-beam 14 GeV)			
Calibration factor	S	128	
Temporal resolution (rms)	$\sigma_{t,r}$	$\sim$2	fs
Energy resolution (rms)	$\sigma_{E,r}$	100	keV

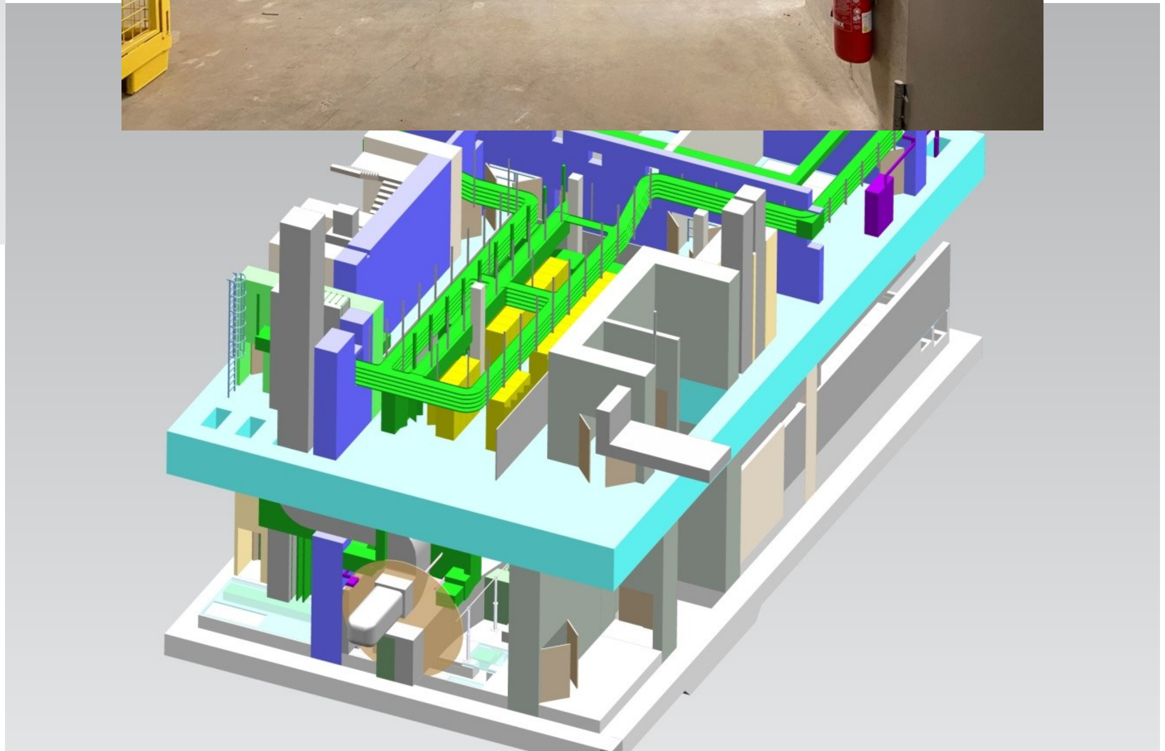
Phys. Rev. ST Accel. Beams 14, 120701 (2011)

XS2



- Space available for 3 RF station similar to the ARES setup

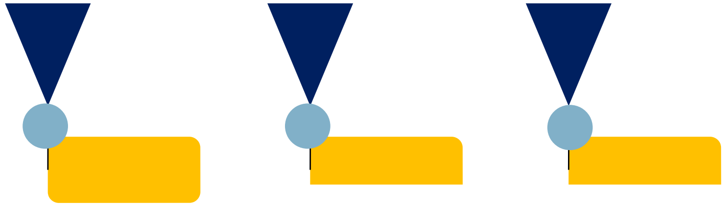




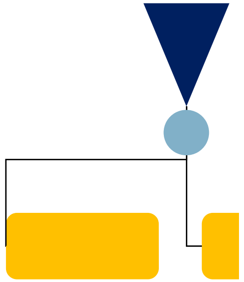
- Available space for support hardware (pulse transformers, controls, …) upstairs needs to be evaluated

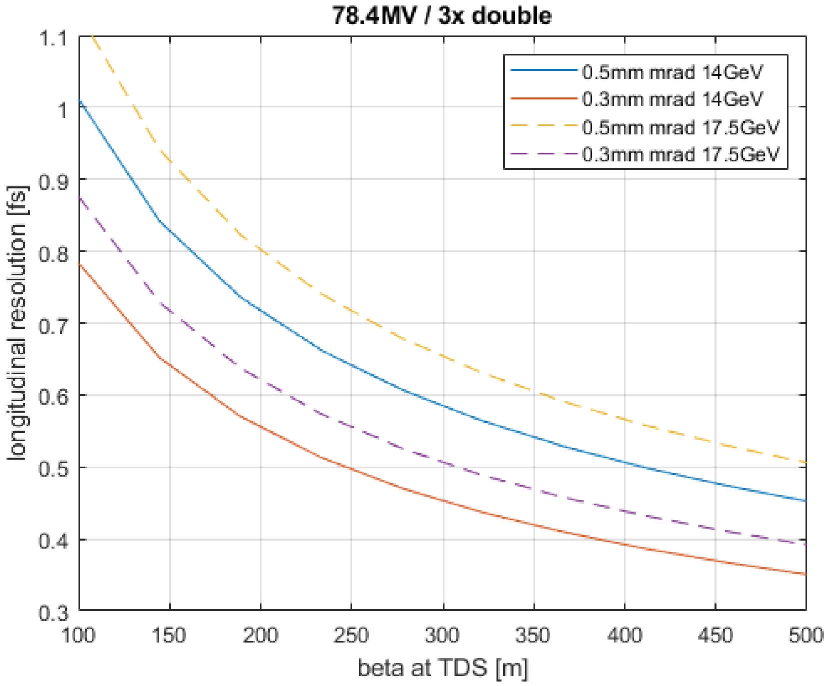
RF Configuration options

- One klystron per structure (e.g. Ares)



- 3dB splitter





- Single or double structure configuration per RF station
- 6MW (or 7.5MW) klystron preferable since a 50MW klystron is very large and difficult to operate in the accelerator tunnel
- BOC at each RF station
- mplex waveguide system in double configuration

6MW	voltage	14GeV	17.5GeV
3x single 1m	55.5MV	1.43fs	1.60fs
3x double 1m	78.4MV	1.01fs	1.13fs
7.5MW	**voltage**	**14GeV**	**17.5GeV**
3x single 1m	62.0MV	1.28fs	1.43fs
3x double 1m	87.7MV	0.90fs	1.01fs

15% losses

100m beta at TDS
0.5mm mrad