
WIR SCHAFFEN WISSEN – HEUTE FÜR MORGEN

Sven Reiche :: SwissFEL :: Paul Scherrer Institut

Design Strategies for Athos

5-Way Meeting, Pohang, Oct 2016

Outlook

- **Switchyard Design Consideration**

Work done by Natalia Miles

- **Dechirper**

Work done by Simona Bettoni

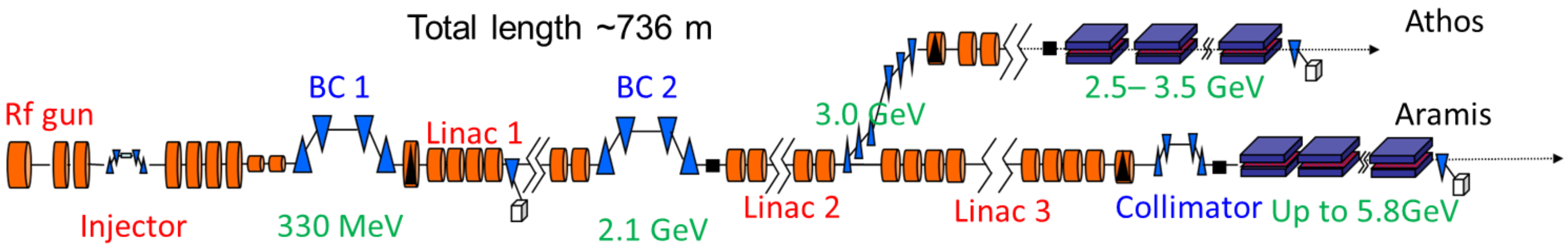
- **ATHOS Undulator Optimization**

Work done by Eduard Prat and myself

- **Transverse Deflector**

Work done by Eduard Prat and Paolo Craievich

Athos: the soft X-ray beamline of SwissFEL



- SwissFEL will serve two beamlines:
  - Aramis: 0.1-0.7 nm. Commissioning starts now, first light in 2017.
  - Athos: 0.65-5 nm. First FEL light expected for 2020
- e^- charge: 10 – 200 pC → pulse length: 2 – 30 fs
- Athos undulators:
  - APPLE devices, K = 0.9-3.5, λ_u= 38 mm (Recent studies might suggest to increase period to 40 nm and inject at higher energy 3.15 GeV)
  - Module length is 2 m, 16 modules available from beginning
  - Installed chicanes between the modules, inter-undulator space is 0.8 m
  - Allow for special configurations, e.g. transverse-gradient undulator (TGU) and continuous taper

Typical simulation parameters

Parameter	Value
e^- charge	200 pC
Current profile	Flat
Peak current	2-3 kA
Pulse duration	67-100 fs
e^- Energy	2.5-3.5 GeV
Emittance	300 nm
Energy spread	350 keV

Almost all simulations presented here are with λ_u= 40 mm (equivalent results)

Basic Features of Switchyard

- Simplified Layout of the Aramis and Athos beamlines:

Less compression in BC2 to 50% the Aramis bunch length, mitigating CSR effects in switchyard

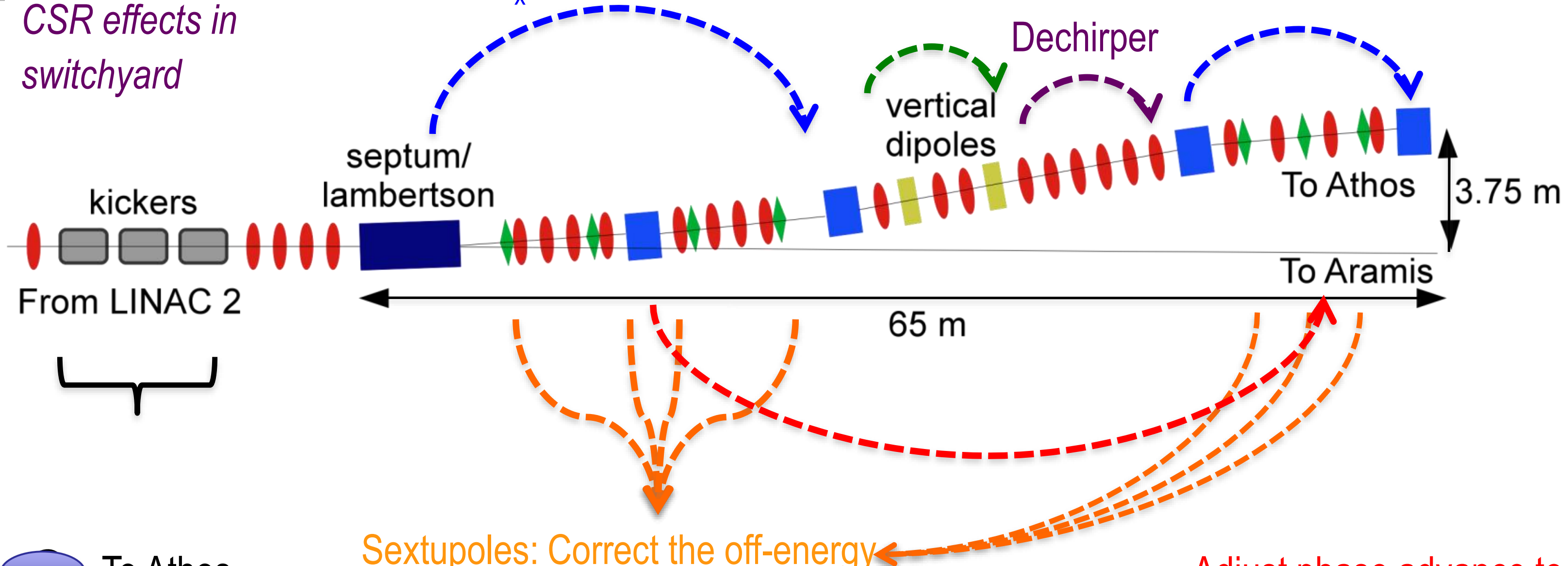
Net bend = 5 deg.

Tune R_{56} by choosing D_x in the center

Lower the beamline by 10 mm and close D_y and D_y'

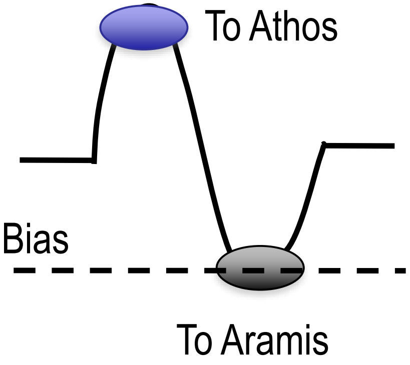
Net bend = -5 deg.

Energy Collimation (D_x>0.2 m → 1%)



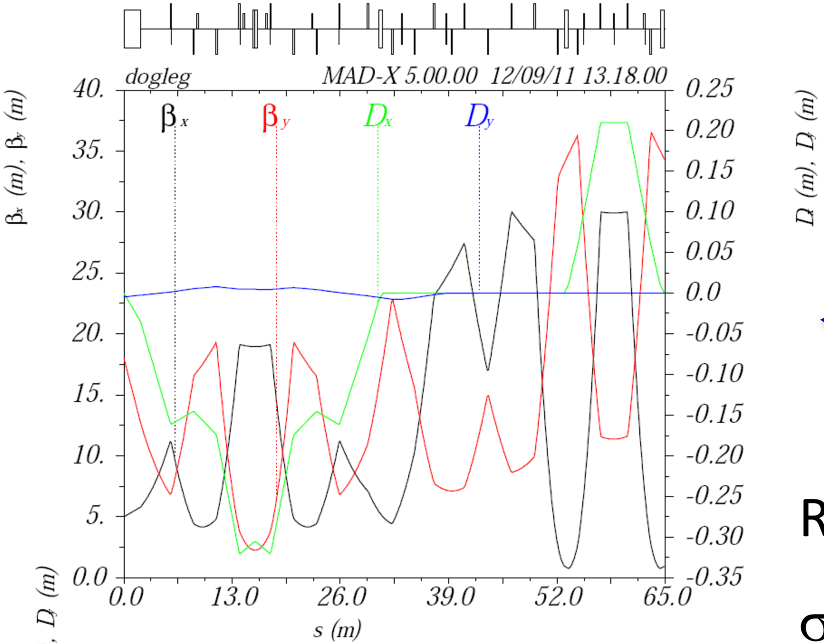
Sextupoles: Correct the off-energy particle's orbit

Adjust phase advance to compensate for CSR



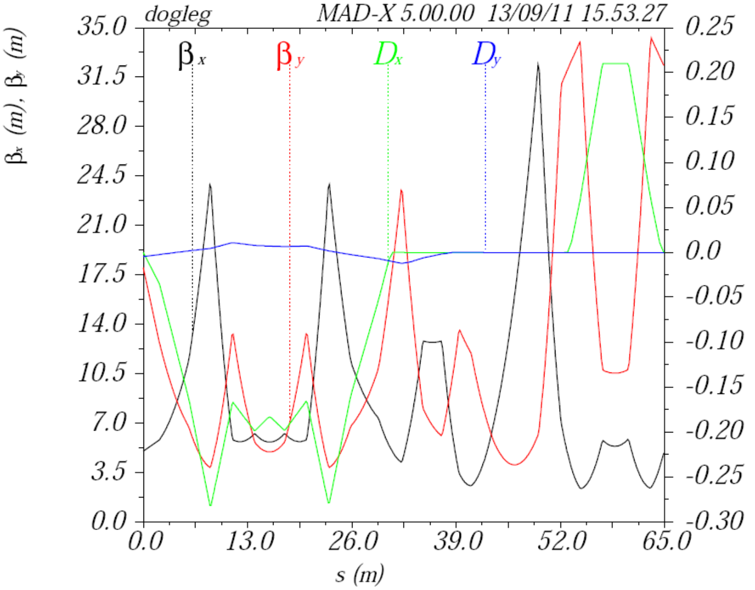
Requirement:	Kickers shot-to-shot jitter < 40 ppm
$\Delta z < 0.1\sigma$ or	Septum/Lambertson shot-to-shot jitter < 10 ppm
$\Delta\varepsilon_z < 0.01\varepsilon_0$	Quadrupole field jitter < 200 ppm

Linear Lattice



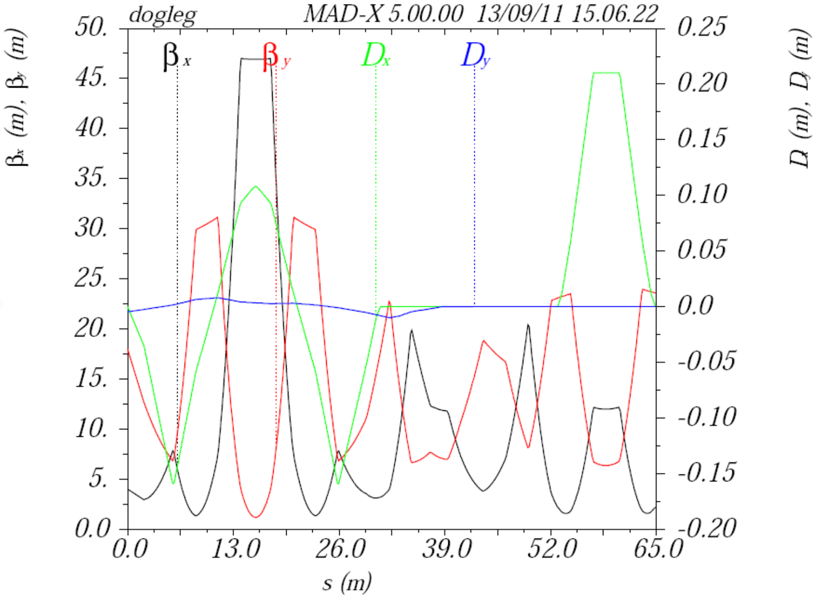
R_{56} = 6 mm

σ_s = 16.4 μm



R_{56} = -1 mm

σ_s = 7.3 μm



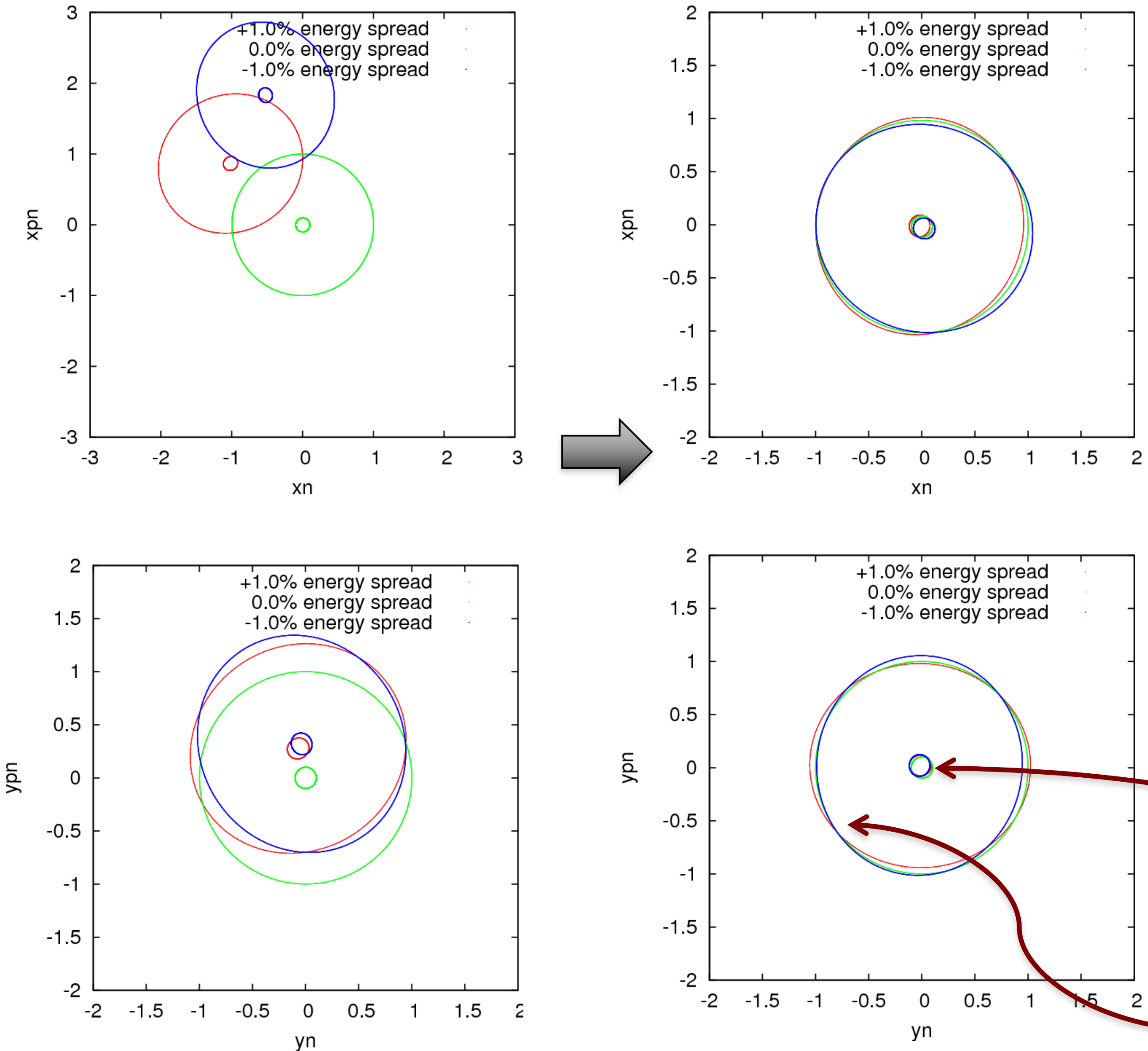
R_{56} = 4 mm

σ_s = 13.7 μm

Orbit Correction with Sextupoles: Case R_{56} = 4 mm

Before

After



Projected Emittance Blow-up

σ_δ	$\Delta\varepsilon_x$	$\Delta\varepsilon_y$
0.1 %	-7%	+0.4%
0.5%	-7%	+0.4%
1%	- 7%	+0.4%
2%	-2.4%	+4.8%

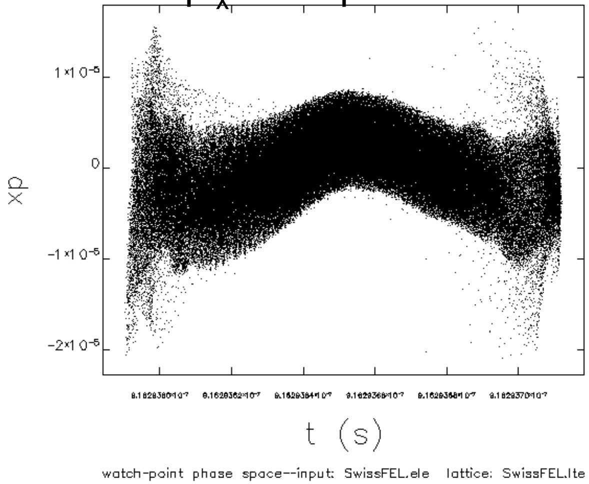
0.1 σ and

1.0 σ circles

CSR kicks compensation: Switchyard

Initial

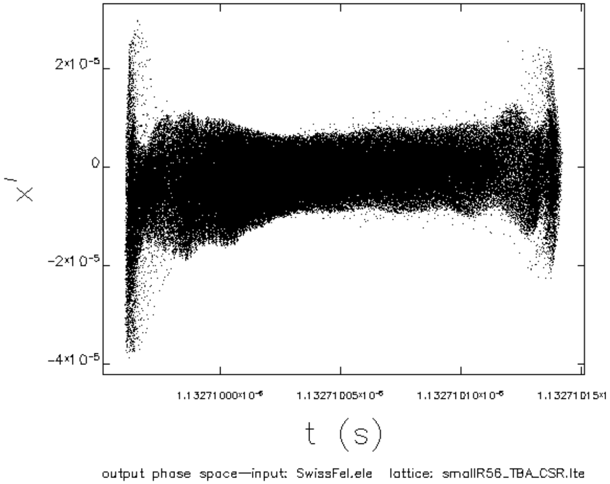
$\gamma\varepsilon_x$ = 0.4 µm rad



Increased due to shearing of slices by CSR

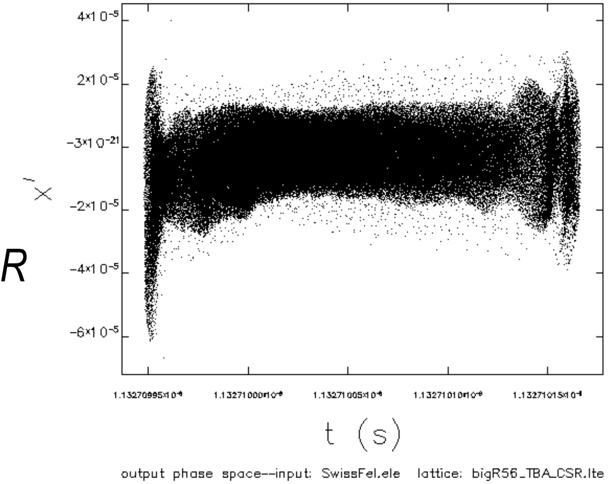
R_{56} = 4 mm

$\gamma\varepsilon_x$ = 0.36 µm rad



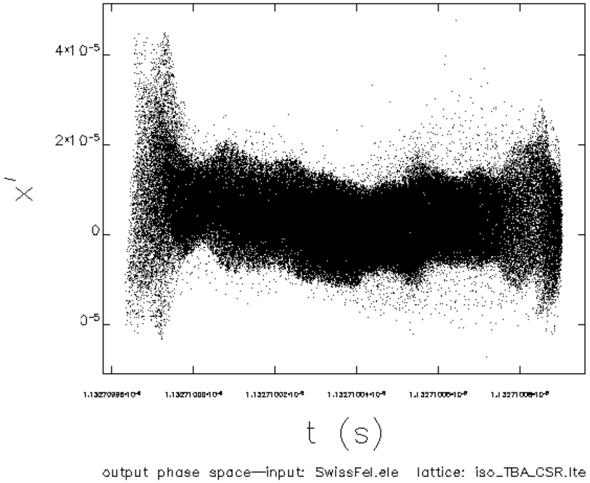
R_{56} = 6 mm

$\gamma\varepsilon_x$ = 0.34 µm rad

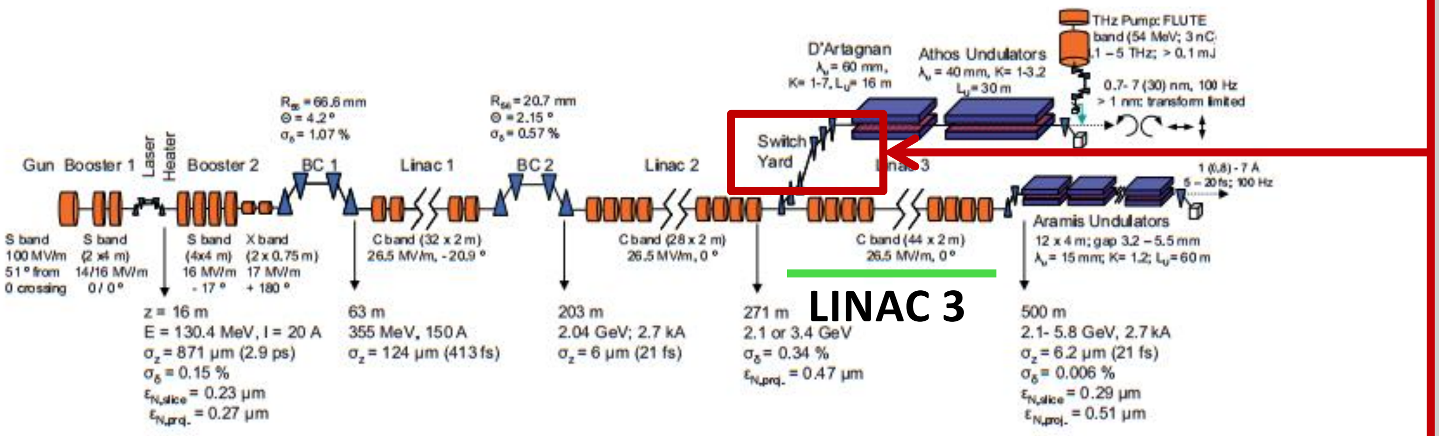


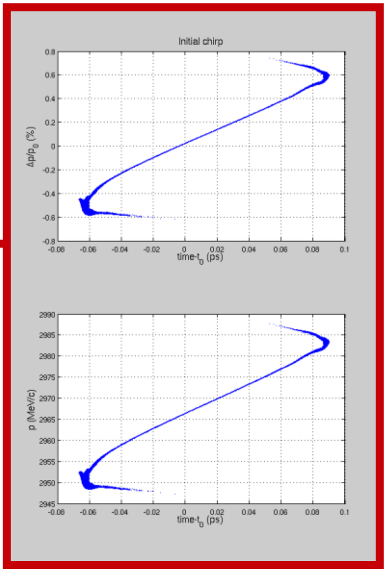
R_{56} = -1 mm

$\gamma\varepsilon_x$ = 0.38 µm rad



Location and Space Constraints





- Aramis line → we compensate for the residual energy chirp at the Aramis line with the wakefield of LINAC 3
- Athos line → we have a residual chirp of 1.1% at 3 GeV (and 0.7% in the new lattice)

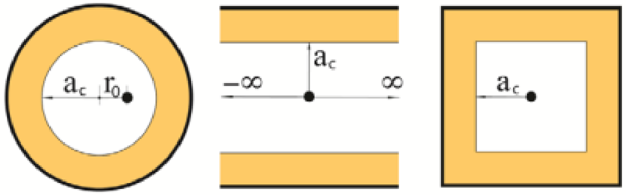
E (GeV)	Full bunch length (µm)	Energy chirp (relative)	Peak current (kA)
3	50	1.1* %-0.7 %	3

CONSIDERED OPTIONS

- Considered several geometries:
  - Corrugated flat
  - Corrugated round
  - Square flat
  - Dielectric layer
- For each of them different geometrical factors on the amplitude

Cherenkov loss factor of short relativistic bunches: general approach

S.S. Baturin[1], A.D. Kanareykin[1,2]



cylindrical	planar	square
$\kappa_c = \frac{Z_0 c}{2\pi a_c^2}$	$\kappa_p = \frac{Z_0 c}{2\pi a_c^2}\frac{\pi^2}{16}$	$\kappa_{sq} = 0.86\frac{Z_0 c}{2\pi a_c^2}$

COMBINATION: RESULTS (1.1% chirp)

$L_{OK}(a = 1.5\ mm)$:

- Flat corr: 17.5 m
- Cyl corr: 11 m
- Square corr: 12.5 m
- Dielectric round: 11.3 m

Flat corrugated	Cylindrical corrugated	Square corrugated	Dielectric round	Compensation
2+2 = 4 m	0	0	2+2 = 4 m	**0.58**
8 m	0	0	0	**0.46**
0	8 m	0	0	**0.73**
0	0	0	8 m	**0.67**
0	0	8 m	0	**0.64**

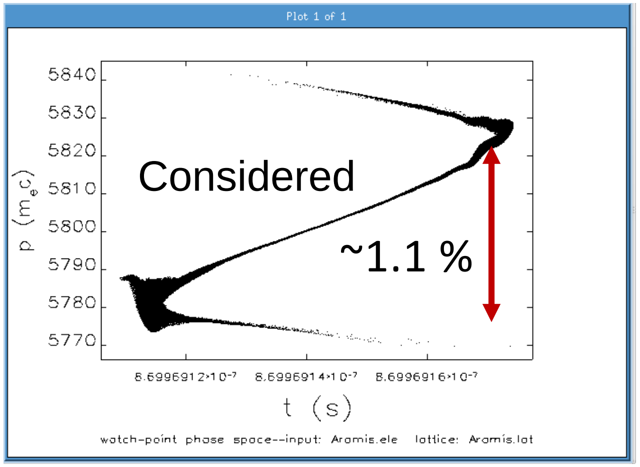
$L_{OK}(a = 1.25\ mm)$:

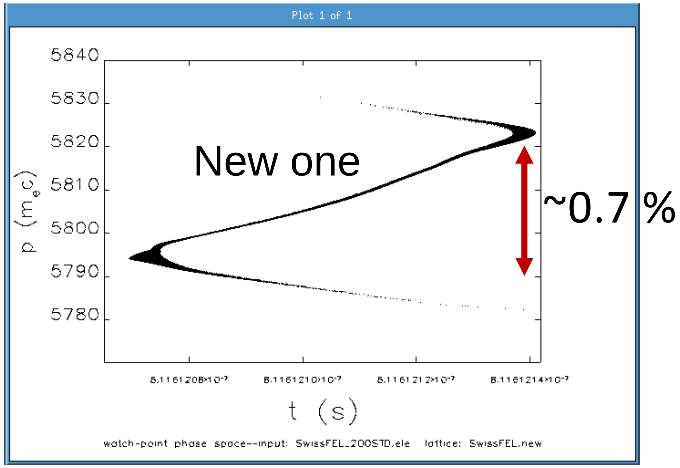
- Flat corr: 12.2 m
- Cyl corr: 7.5 m
- Square corr: 8.5 m
- Dielectric round: 8 m

Flat corrugated	Cylindrical corrugated	Square corrugated	Dielectric round	Compensation
2+2 = 4 m	0	0	2+2 = 4 m	**0.83**
8 m	0	0	0	**0.66**
0	8 m	0	0	**1.07**
0	0	0	8 m	**1.0**
0	0	8 m	0	**0.94**

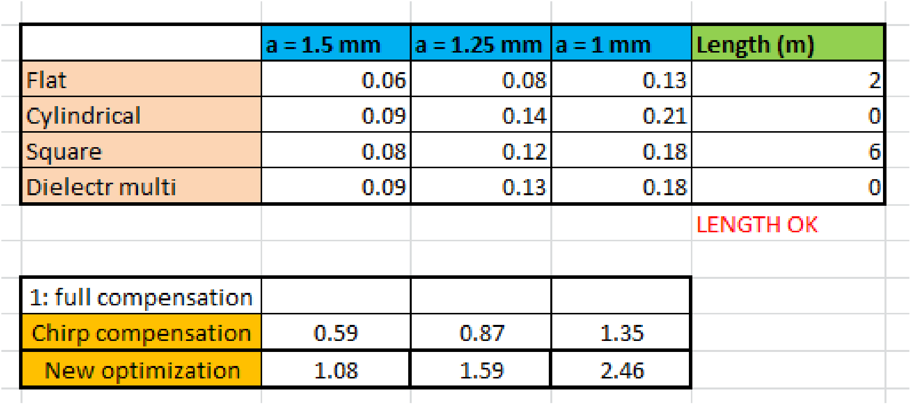
The sum of the configurations must give 1 to perfectly compensate the chirp

COMBINATION: RESULTS (0.7% chirp)





Assuming the new input distribution



	a = 1.5 mm	a = 1.25 mm	a = 1 mm	Length (m)
Flat	0.06	0.08	0.13	2
Cylindrical	0.09	0.14	0.21	0
Square	0.08	0.12	0.18	6
Dielectr multi	0.09	0.13	0.18	0

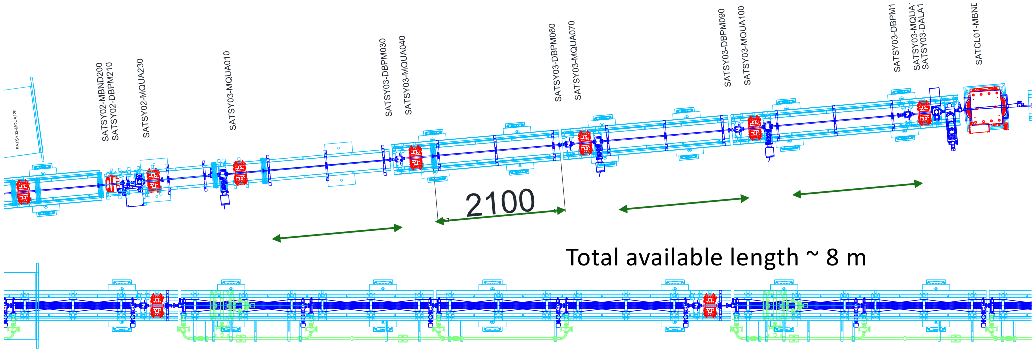
LENGTH OK

1: full compensation			
Chirp compensation	0.59	0.87	1.35
New optimization	1.08	1.59	2.46

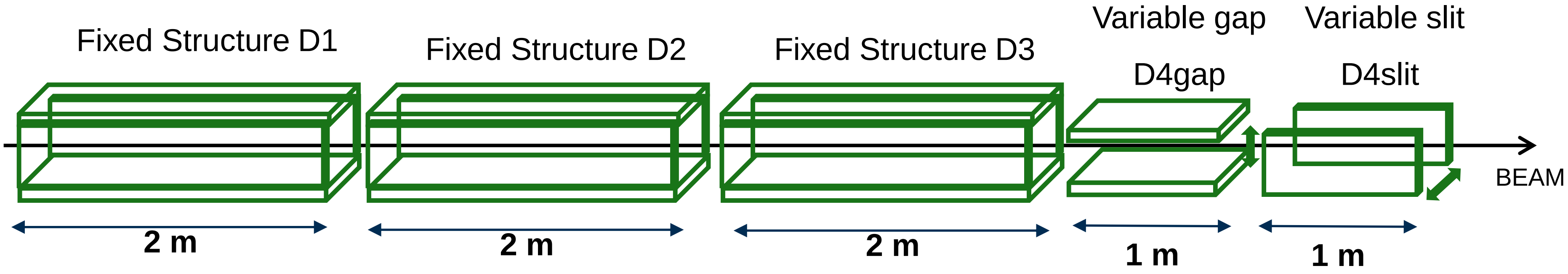
The sum of the configurations must give 1 to perfectly compensate the chirp

POSSIBLE SOLUTION

- We think to use this scheme:

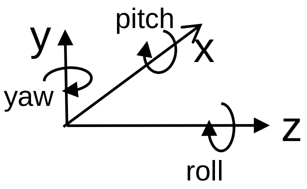


Total available length ~ 8 m



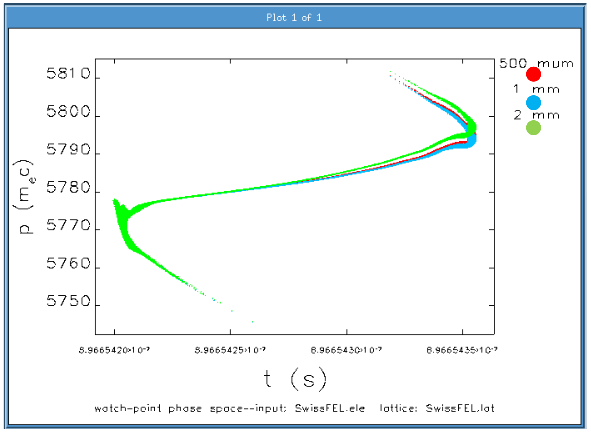
- 4 modules of 2 m length each: fixed or movable?
- 2 modules 1 m length each: movable

All modules movable in: x, y, pitch, yaw, roll



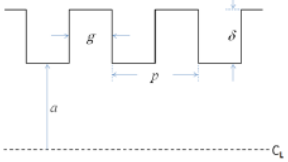
POSSIBLE GEOMETRY

Beam longitudinal phase space assuming wavelengths of the wakefield



The wavelength of the wakefield is given by:

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

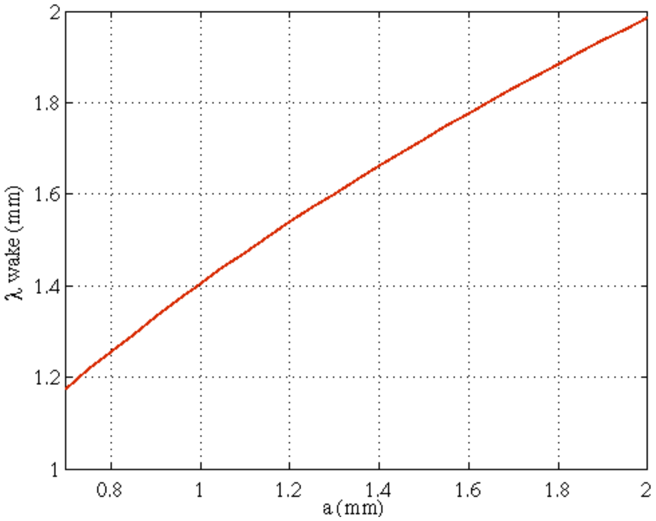


Conditions to be satisfied:

with p as the corrugation period, and g as the gap (see **Figure 1**). This wake function is reasonably accurate for $\delta, p << a$ and $\delta \geq p$, and its transient regime, $0.5a^2/\sigma_z << L$, is very short.

A possible geometry:

g (μm)	p (μm)	δ (μm)	a (mm)	λ (mm)
100	200	200	1.25	1.57



Overview of operation modes

Standard modes:

- ➢SASE
- ➢Self-seeding

Novel operation modes :

1. Slicing (HHG source OR laser + continuous taper)
2. Optical klystron (chicanes)
3. HB-SASE (chicanes)
4. Short and high-power pulses (chicanes + beam tilt OR chicanes + slotted foil)
5. Two-color FEL pulses (beam tilt + self-seeding chicane)
6. Large bandwidth FEL pulses (beam tilt + TGU)

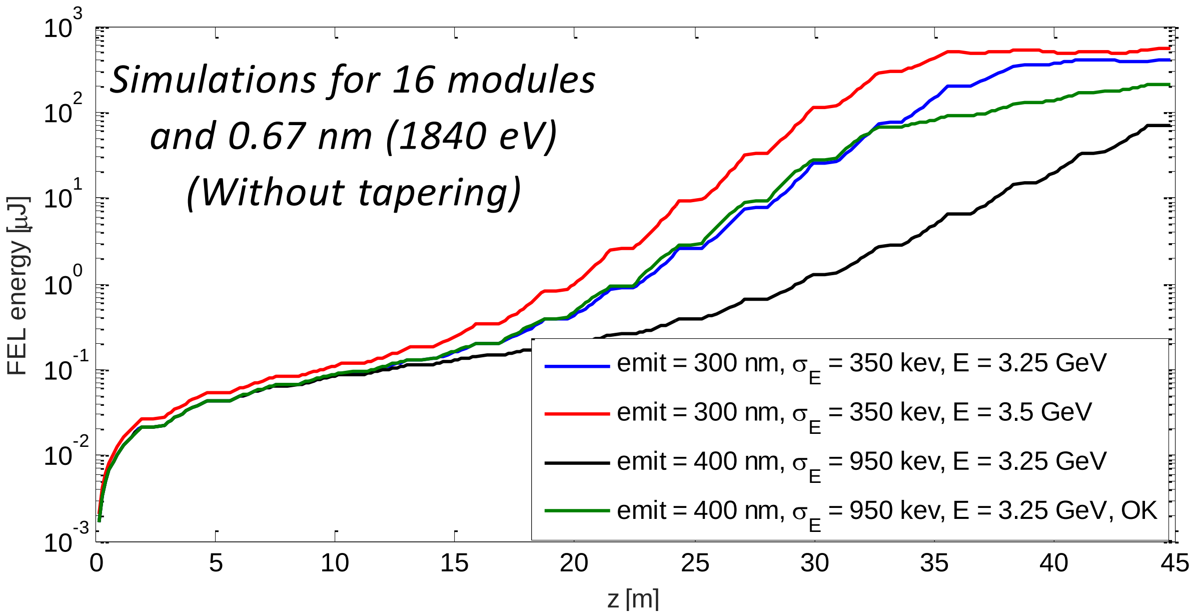
- Chicanes and beam tilt are fundamental
- This talk covers 6. The rest has been presented in previous meetings and conferences, more info is available in the back-up slides
- Self-seeding and external laser initially unavailable due to budget issues
  - In green: initially available modes
  - In red: available modes in future upgrade with self-seeding and laser

Baseline and future upgrade

- Due to budget issues, at the beginning we will have 1 RF station (instead of 2), 16 undulator modules (instead of 20), no external laser, and self-seeding chicane without monochromator

	Baseline	Future upgrade
e^- Energy	2.75-3.25 GeV	2.5-3.5 GeV
Wavelength range	0.66 nm (K=0.9) 4.67 nm (K=3.5)	0.57 nm (K=0.9) 5.66 nm (K=3.5)
Undulator modules	16	20
Self-seeding chicane	Only chicane	Chicane + monochromator
External laser	No	Yes

- Wavelength range is reduced and FEL performance is degraded due to reduced energy
- Initial parameters enough to reach saturation for Si edge (1840 eV or 0.67 nm)
- Need to use optical klystron if beam parameters are degraded



Simulations for 16 modules and 0.67 nm (1840 eV) (Without tapering)

Beam tilt generation

We consider 3 methods :

- **Transverse deflecting structure (TDS)**
- **Transverse wakefields**
- **Adding dispersion to an energy chirped beam**

To generate 1 mm offset along the nominal bunch (sufficient for the different applications):

- **TDS**: needs 72 MV (SwissFEL TDS has 70 MV), energy spread increases to 600 keV, sensitive to time jitter, TDS not available for Athos.
- **Wakefields**: possible with dechirper, energy spread increases 1.9 MeV at the tail, nonlinear tilt.
- **Dispersion**: a quad in dispersion section is enough, energy spread increases to 600 keV (avoidable with more complicated lattice), emittance increases to 370 nm

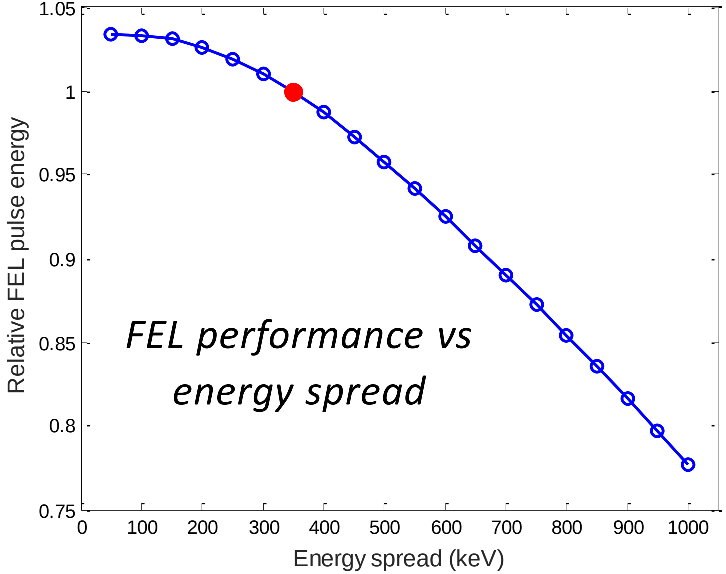
- ➢ FEL performance is more sensitive to emittance than energy spread. Deteriorating effects are acceptable
- ➢ Best method will depend on parameters such as required tilt, beam quality, and FEL requirements (i.e. nonlinear tilt with wakefields works for 2 colors and LB but with asymmetric FEL power results)

[E. Prat et al, NIMA in press (2016)]

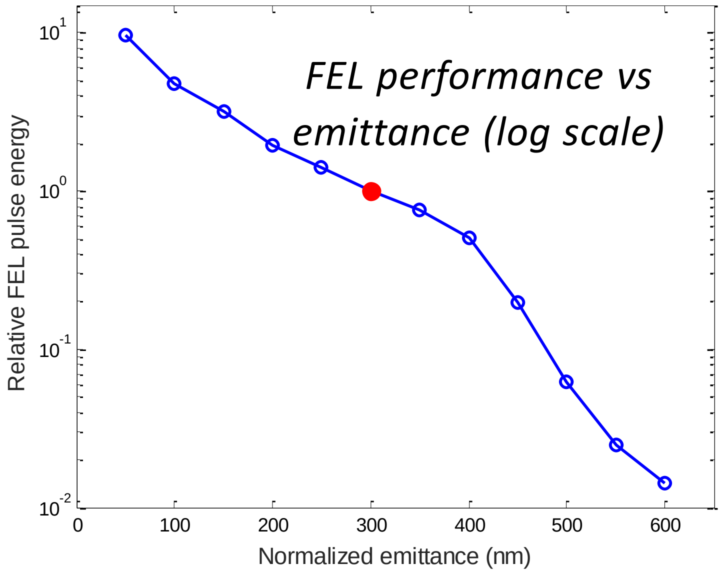
I = 3 kA, λ = 1 nm

14 modules (enough for saturation)

Reference case: 350 kev, 300 nm



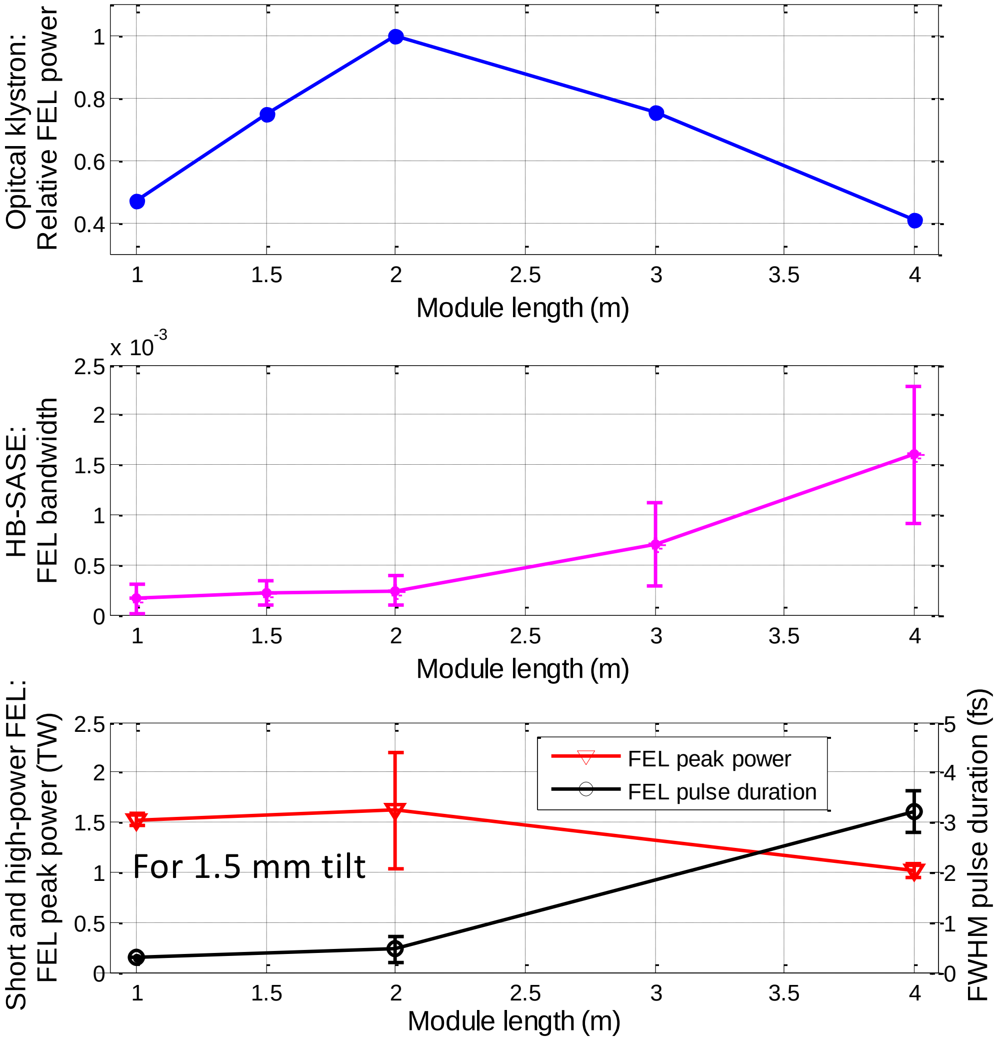
FEL performance vs energy spread



FEL performance vs emittance (log scale)

Optimization of undulator module length

Summary of FEL performance as a function of the undulator module length



[E. Prat et al, JSR 23, 861 (2016)]

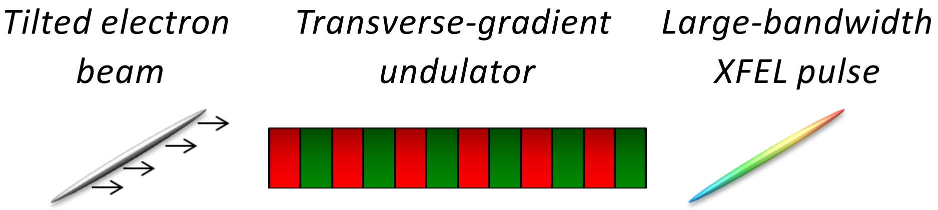
Based on physics and costs

Final module length is 2 m

(original design was with 4 m)

Large bandwidth FEL pulses

- Idea: In a TGU there is a dependence of the undulator field on the transverse position. A transversely-tilted beam traveling through a TGU will produce broadband XFEL radiation



- The method is very easy to tune (by changing tilt and/or TGU amplitude)
- To allow that every slice lases at the same frequency the beam needs to travel parallel: initial tilt only in offset & no external focusing → (tolerable) decrease of FEL performance
- Additional possibilities of the scheme:
  - Multiple colors with slotted foil at the undulator entrance
  - FEL pulse compression (sign of the chirp can be controlled)
- Alternative method: generation of energy-chirped electron beam optimizing the compression setup (overcompression, wakefields) and the laser distribution at the source. Results: ~3% bandwidth for 0.1 nm and 5.8 GeV @ Aramis

[E. Prat, M. Calvi, and S. Reiche, JSR 23, 874 (2016)]

Large bandwidth FEL pulses: simulations

Continuous undulator of 40 m without focusing (β_x=40m, β_y=35m)

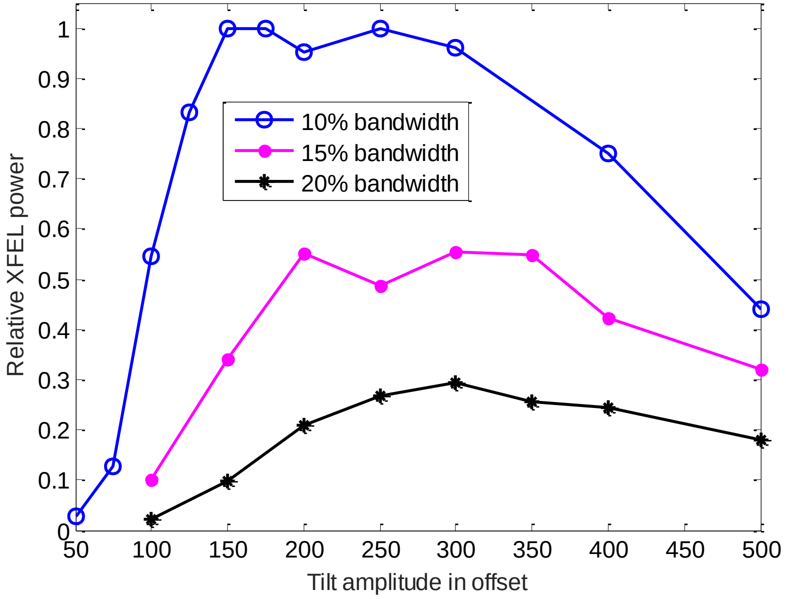
Simulation parameters: I = 3 kA, σ_E = 350 keV

Central wavelength: 1 nm

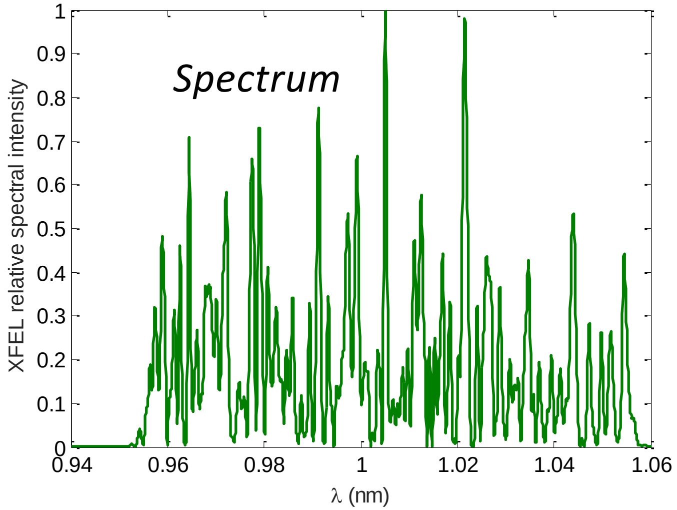
A gradient of 48 m^{-1} and an offset variation of 2.5 mm along the bunch produces FEL radiation with 10 % bandwidth and peak powers of ~10 GW

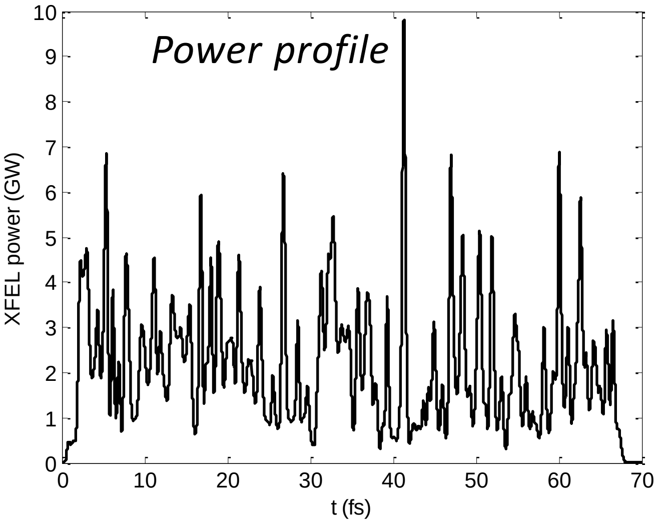
Performance for different optimum gradient/tilt values

- Too strong tilt: radiation slips out of the electron beam
- Too strong gradient: wavelength change within slice transverse size is too large



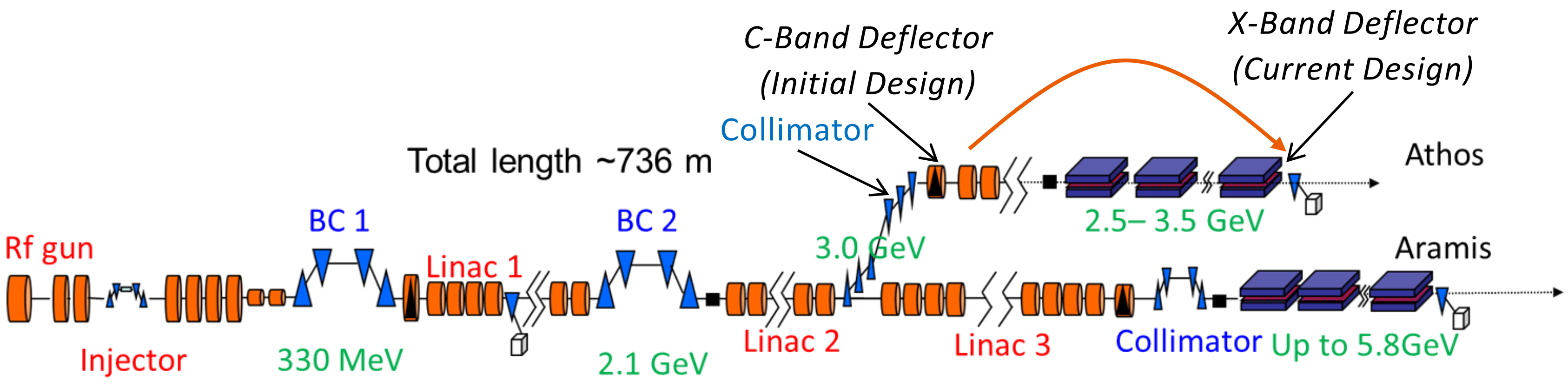
We can obtain XFEL pulses with 20 % bandwidth and few GW peak power





PAUL SCHERRER INSTITUT

Transverse Deflector



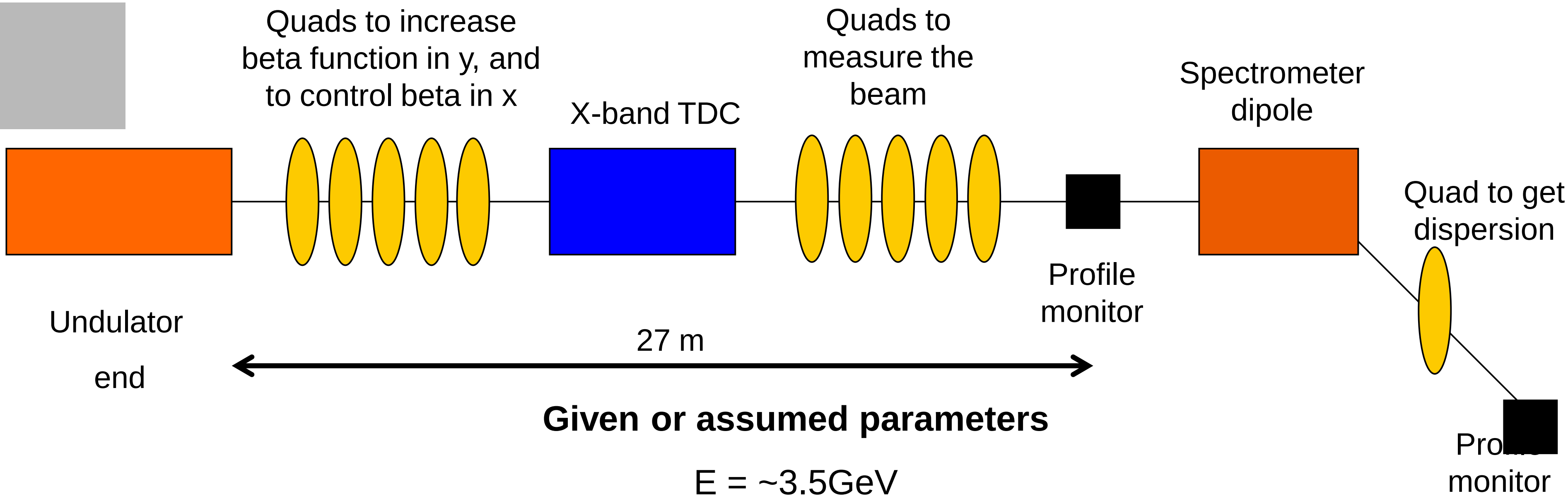
- General Layout of Athos (and Aramis) has the problem:
  - Needs vertical streaking for measuring slice parameter of bending plane
  - Needs horizontal streaking for longitudinal phase space in vertical beam dump
- Problem is solved for Aramis due to the energy resolution of the succeeding energy collimator, while in Athos the energy collimator comes first

Collaboration with CERN and DESY to build an X-bad Deflector, where the streaking direction can be adjusted with RF phase adjustment of the couplers.

- Solves the problem of phase space and slice emittance measurements
- Allows for single shot FEL pulse measurement a la LCLS XTCAV
- Possible short term replacement of klystron of X-band linearizer

Lattice concept

Wanted resolution: ~0.8fs (0.25 μm)



Quads to increase beta function in y, and to control beta in x

X-band TDC

Quads to measure the beam

Spectrometer dipole

Quad to get dispersion

Profile monitor

Undulator end

27 m

Profile monitor

Given or assumed parameters

$E = \sim 3.5\,\mathrm{GeV}$

$Q = 200\,\mathrm{pC}$: $\varepsilon = 0.4\,\mu\mathrm{m}/\gamma$

$Q = 10\,\mathrm{pC}$: $\varepsilon = 0.3\,\mu\mathrm{m}/\gamma$

X-band:cavity

Assumed available voltage: **~50MV**

Assumed occupied space: 2.4 m

Required β-function at the deflector: **> 50m**

Conclusion

Athos Beamline most challenging beamline for the design:

- Complex control of R56 with optics while preserving beam quality
- Length contraints for dechirper yield tight alignment tolerances
- Shorter undulator modules in combination with small chicanes allow for more modes but are more difficult to set-up
- Post undulator TDS as major diagnostic for setting up and running Athos.

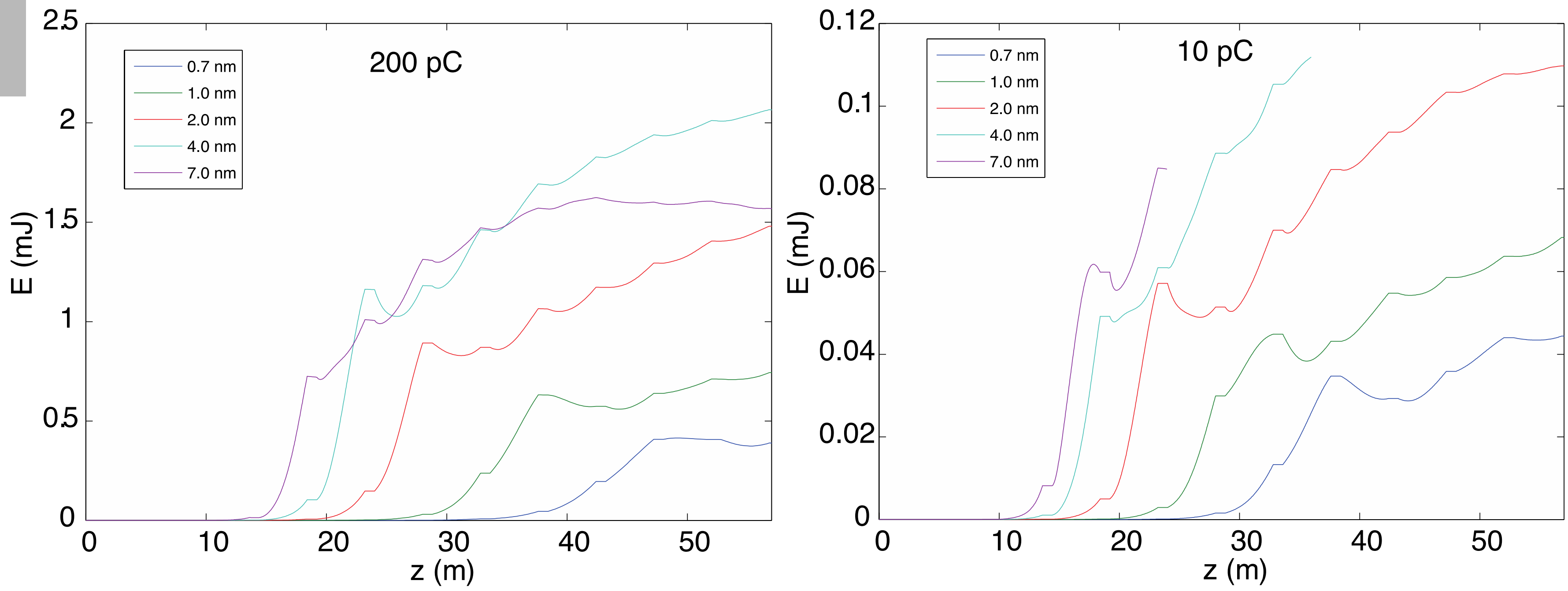
Back-up slides

Summary

Mode	Pulse Energy	#Photons @ 1 nm	Pulse Length (RMS)	Bandwidth	Comment
SASE (200pC)	>1mJ	$5 \cdot 10^{12}$	30 fs	0.1-0.4%	
SASE (10pC)	>50 µJ (10 pC)	$2.5 \cdot 10^{11}$	2 fs	0.1-0.4%	
Self-Seeding	>1mJ	$5 \cdot 10^{12}$	30 fs	< 1e-4	Above 1nm, 200 pC only
Optical Klystron	As SASE	$5 \cdot 10^{12}$	As SASE	As SASE	More length for taper
HB-SASE	As SASE	$5 \cdot 10^{12}$	As SASE	0.02-0.04%	Can also be configured for pulse trains
TW Pulse	> 1mJ	$5 \cdot 10^{12}$	~1 fs	1% FWHM	200 pC bunch
Two Colors	2 x >50 µJ	2 x $2.5 \cdot 10^{11}$	2 x 2-10 fs	0.2%, tuning range: factor 5	Based on 200 pC bunch
Large Bandwidth	>0.5 mJ	$2.5 \cdot 10^{12}$	30 fs	>10% FW	200 pC only
HHG-Seed	1 µJ (every 3 fs)	$5 \cdot 10^{9}$	< fs per pulse	0.1-0.4 %	Sub-fs locking
Slicing	1 µJ (every 3 fs)	$5 \cdot 10^{9}$	< fs per pulse	0.1-0.4 %	Sub-fs locking

Baseline performance (SASE)

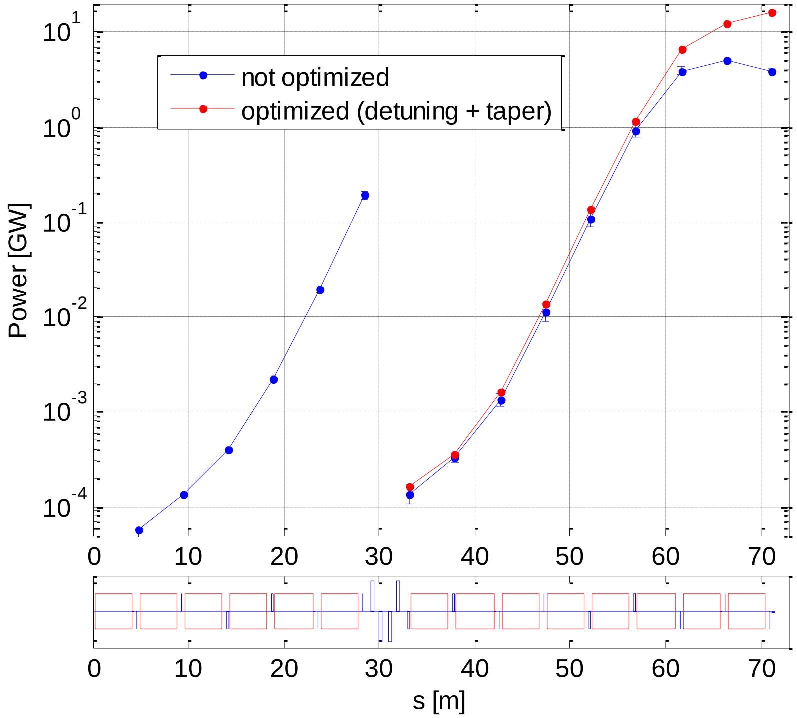
- Old design beam parameters (before measurements at SwissFEL Injector Test Facility):
  I = 2 kA, emittance = 430 nm (200 pC), undulator module is 4 m long

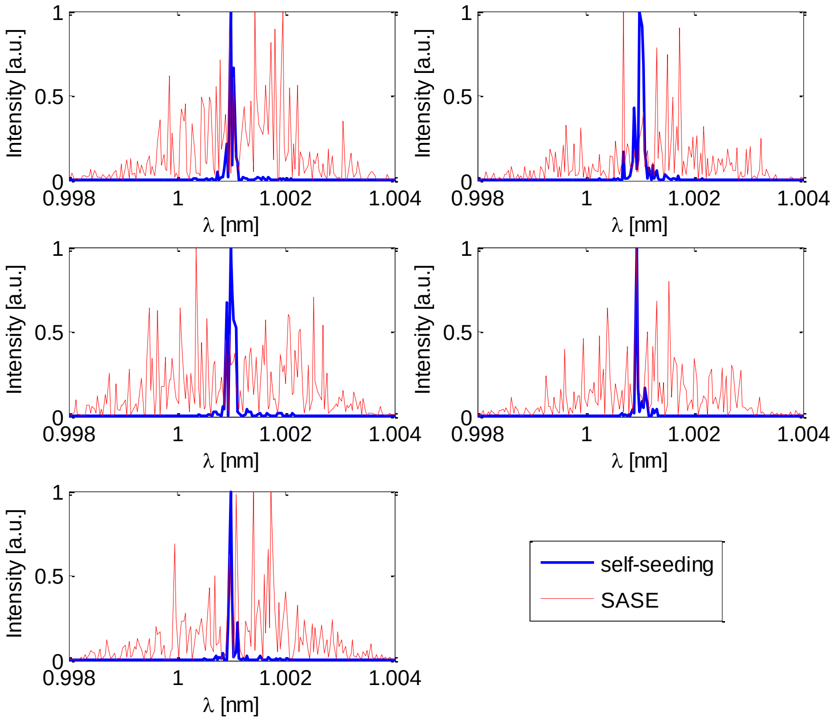


- Maximum saturation length is 48 m for 0.7 nm
- More than 1 mJ pulse energy for 2 nm or longer (results not optimized for post-saturation taper)
- Pulse length between 2 fs (Q = 10 pC) and 30 fs (Q = 200 pC)
- Bandwidth: 0.1 – 0.4%.

Baseline performance (self-seeding)

Q= 200 pC, I =2 kA, emittance = 430 nm, undulator module is 4 m long





Final FEL pulse energy: 1.6 mJ

Bandwidth is reduced by a factor of 20

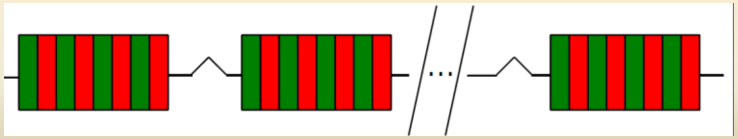
Monochromator:

- 2% Transmission
- 5000 resolving power

[E. Prat, D. Dunning and S. Reiche, FEL12 (TUPD21)]

CHIC design for FELs

Chicanes for High power and Improved Coherence



We propose to include small chicanes made of dipoles between the undulator modules. Chicanes have two physical effects: longitudinal dispersion (R_{56}) and delay. Benefits:

1. *Reduction of saturation length (more space to taper) using the optical klystron effect (R_{56})*
2. *Increase of brightness using the HB-SASE concept (delay)*
3. *Generation of short and high-power FEL Pulses (TW-as pulses) based on superradiance with a multiple slotted foil or a transversely tilted beam (delay)*

We have optimized the undulator module length for best performance:
Optimal use demands short undulator modules

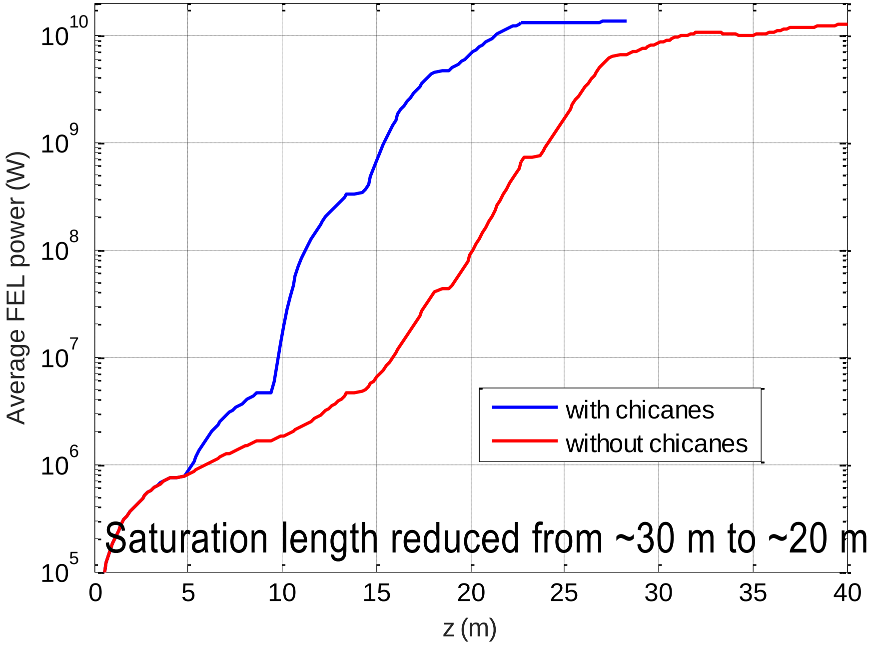
The delay of the chicanes is up to ~1 µm
Present design with permanent magnets: maximum delay of 1.5 µm, total length is 0.2 m

[E. Prat, M. Calvi, R. Ganter, S. Reiche, T. Schietinger, and T. Schmidt, JSR 23, 861 (2016)]]

CHIC: Optical klystron

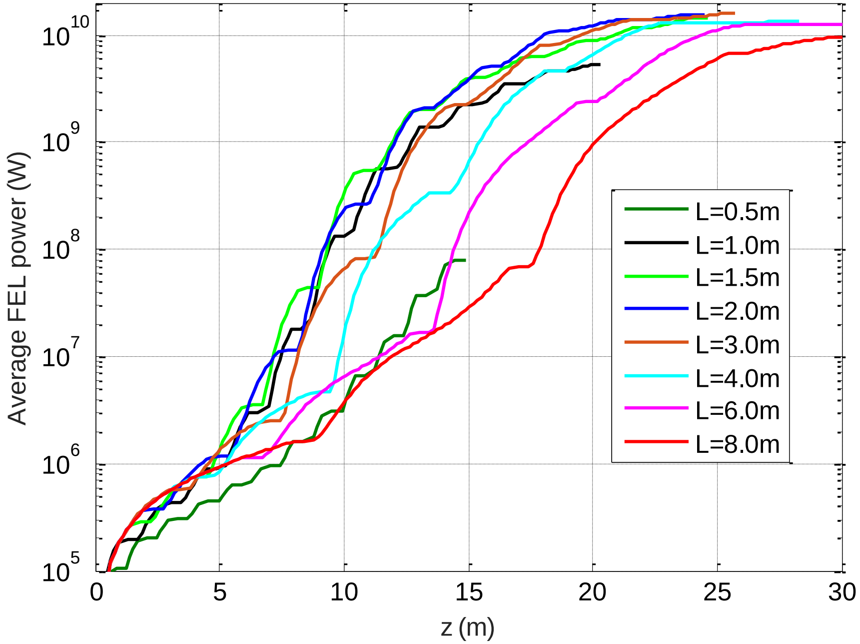
- We scan the delay/R_{56} after each chicane, we take the value that maximizes the FEL power
- We take minimum achievable β-function per each modulator length

FEL along the undulator beamline with and without optical klystron configuration (L = 4 m)



Saturation length reduced from ~30 m to ~20 m

Power along the undulator beamline for the optimized cases



For short modules we are penalized by the poor filling ratio (break section of 0.75 m)

For long modules we are penalized by limited number of sections to apply optical klystron and β-function

Best results for a module length around 2 m

(w/o chicanes the optimum length is 3 m)

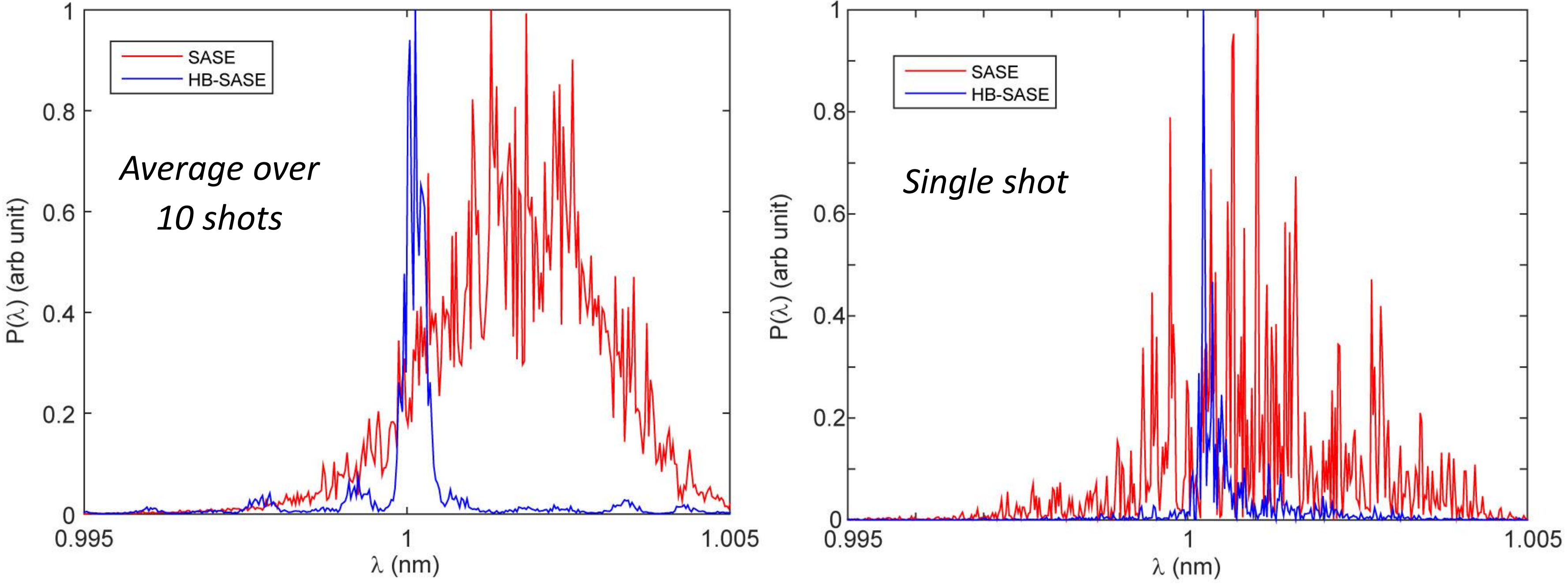
CHIC: HB-SASE

- We consider L=1, 1.5, 2, 3 and 4 m
  - For L<1m low filling ratio penalty is too large
  - For L> 4m HB-SASE does not work
- Per each case we simulated different delay/R_{56} configurations (from higher to lower values to use optical klystron effect)
- For L≤ 2 m the bandwidth gets reduced by about a factor of 10

Simulation results
(average over 10 seeds)

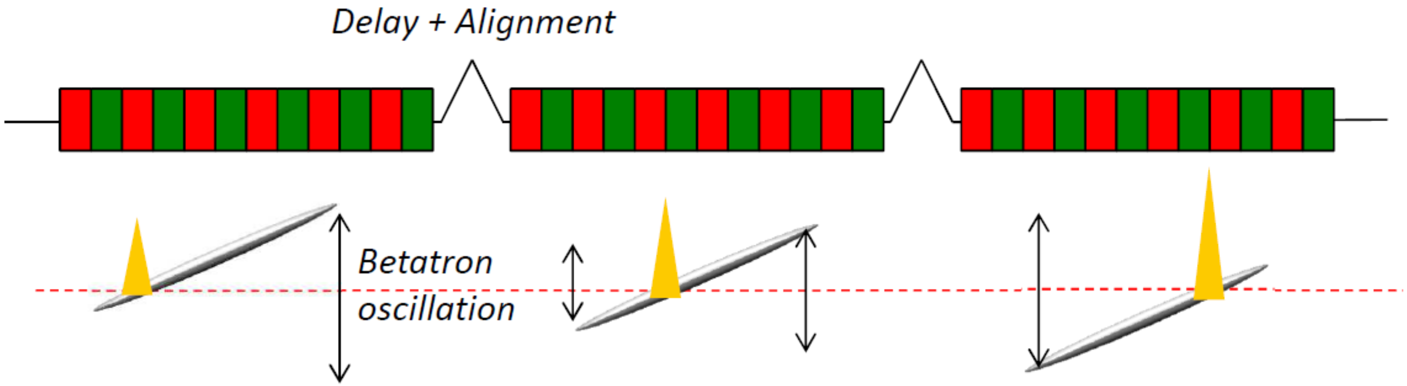
Module length	FWHM Bandwidth $\times 10^{-4}$
L=1m	1.6±1.5
L=1.5m	2.1±1.2
L=2m	2.4±1.5
L=3m	7.0±4.2
L=4m	16.0±6.9
L=2m (SASE)	19.4±10.3

Output spectra for L=1.5 m



CHIC: short and high-power FEL pulses

- There are already some good ideas to achieve shorter pulses by reducing the electron pulse length (e.g. slotted foil, low charge) and using external lasers. Tanaka recently proposed a complicated scheme to get TW-as pulses *[T. Tanaka, PRL 110, 084801 (2013)]*.
- We propose two simpler methods using small chicanes between the modules:
  - With multiple slotted foil in BC *[E. Prat and S. Reiche, PRL 114, 244801 (2015)]*
  - With a tilted beam *[E. Prat, F. Löhl and S. Reiche, PRSTAB 18, 100701 (2015)]*. This method is more efficient and offers better tunability. Results in this talk are for this method.



- The scheme has N undulator sections and (N-1) chicanes. The beam is split in N subpulses
- In the first undulator section only the first subpulse (tail) produces XFEL radiation
- Then the electron beam is delayed and aligned such that the 2nd subpulse overlaps with the XFEL pulse. Only this part is amplified.
- This is repeated until all the electrons have contributed to amplify the short pulse

CHIC: short and high-power FEL pulses

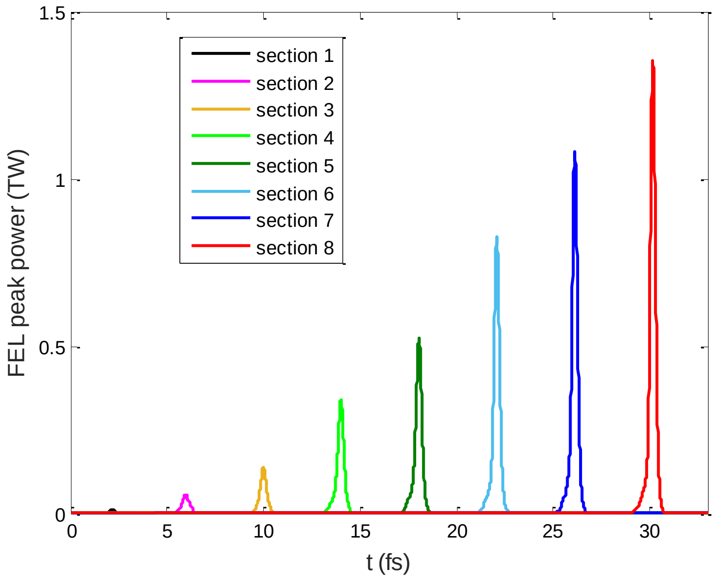
- Simulations: I = 6 kA, λ= 2 nm, 8 undulator sections (7 chicanes)

Results for different module lengths and tilt amplitudes (average over 5 seeds)

L (m)	Offset along the bunch (mm)	Undulator modules	Undulator length (m)	Peak power (TW)	Pulse energy (mJ)	FWHM pulse duration (fs)
4	1.5	11 (4+7*1)	52	1.02± 0.07	2.21± 0.14	3.21± 0.42
4	3	11 (4+7*1)	52	1.40± 0.19	1.81± 0.19	1.92± 0.90
2	1.5	20 (6+7*2)	55	1.62± 0.58	1.01± 0.24	0.46± 0.26
2	3	20 (6+7*2)	55	1.48± 0.20	0.52± 0.05	0.30± 0.01
1	1.5	40 (12+7*4)	70	1.52± 0.06	0.64± 0.02	0.30± 0.01
1	3	40 (12+7*4)	70	0.46± 0.16	0.18± 0.06	0.34± 0.01

- By tuning the tilt amplitude one can choose shorter pulses with less energy or longer but more energetic pulses
- Shorter modules are generally better (stronger focusing, less tilt for same performance, delays can be applied more often…, but longer)

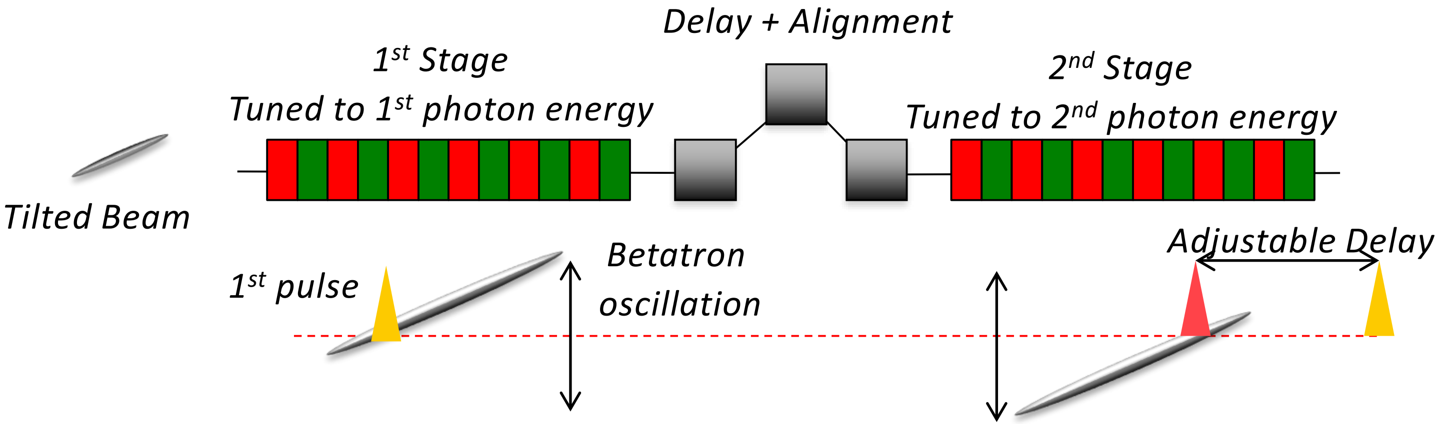
FEL radiation profile after each undulator section for L=2m and a tilt of 3 mm (1 seed)



Two-color FEL pulses

- Existing methods mainly use:
  - Undulators tuned at different *K* (low power, good tunability, long undulator)
  - 2 electron bunches with different energy (high power, limited tunability, short undulator)
- We propose to use a tilted beam, two variable gap undulator sections and a chicane
  1. In the first stage the “tail” is centered and lases at λ_1
  2. The electron beam is delayed and the “head” is realigned
  3. In the second stage the “head” lases at λ_2

[S. Reiche and E. Prat, JSR 23, 869 (2016)]



Delay + Alignment

1st Stage

Tuned to 1st photon energy

2nd Stage

Tuned to 2nd photon energy

Tilted Beam

Betatron oscillation

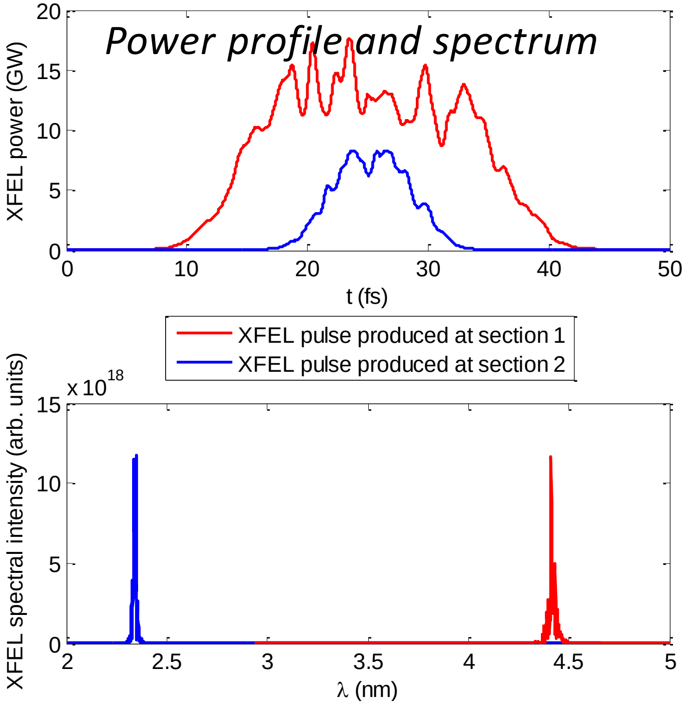
1st pulse

Adjustable Delay

- The method offers high power for both pulses (similar to SASE), great tunability, but it requires a long undulator
- Tunability: beam delay with chicane, wavelength difference with gap, length of each pulse with tilt amplitude and/or focusing strength
- Additional methods for SwissFEL with worse tunability but requiring shorter undulator: two electron bunches with slotted foil, wakefields

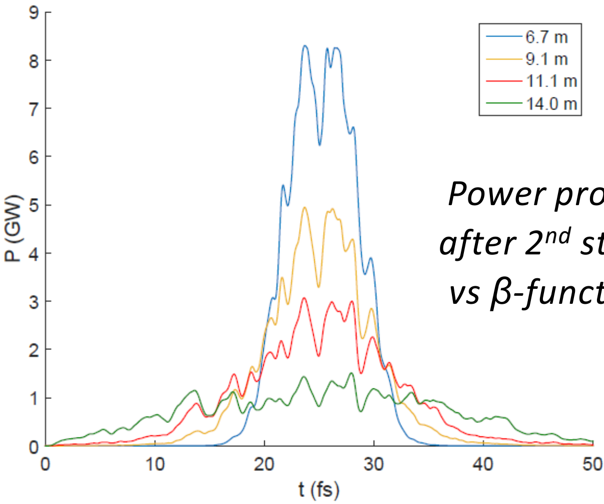
Two-color FEL pulses: simulations

Parameters:
E= 2.91 GeV, I = 2 kA, σ_E= 460 keV
Wavelengths: 4.4 nm (K=3.5) / 2.3 nm (K=2.35)
10 +10 undulator modules in section 1 and 2
(with 8 + 8 modules optical klystron is needed)


Power profile and spectrum

Tunability

Parameters	Values
Individual Pulse Length	2 – 10 fs
Individual Pulse Energy	50 – 250 µJ
Relative Delay	-10 to 1000 fs
Photon energy	Factor 5 (e.g. 240 – 1200 eV)


Power profile after 2nd stage vs β-function

The performance of both colors can be adjusted by using different betatron functions at each stage

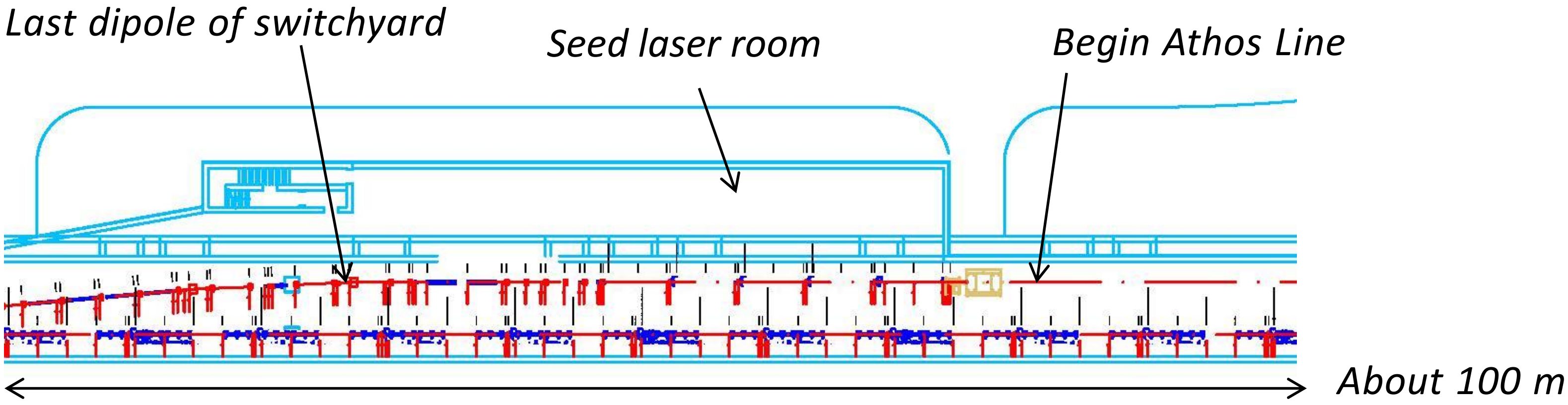
Locking with external laser source

To achieve a better stability between pump laser and FEL signal, the FEL signal is synchronized with the pump signal in the FEL process

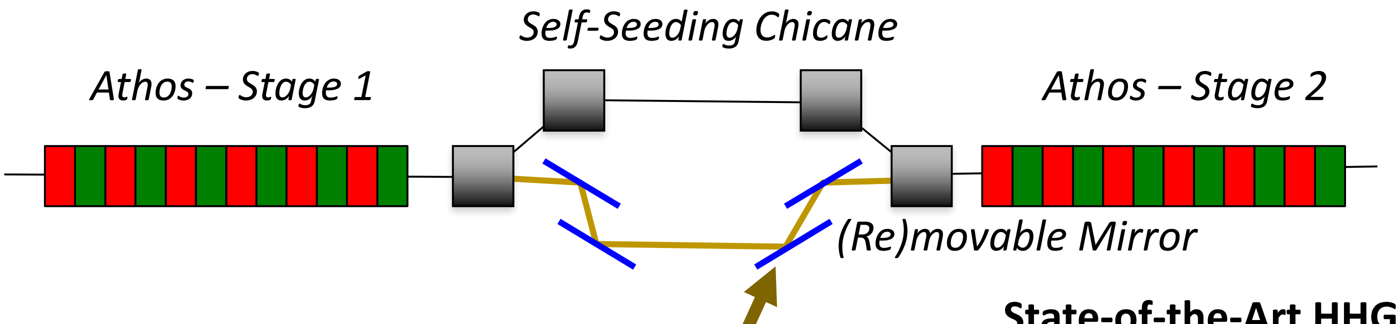
- *Direct Seed*
- *Electron Slicing (energy modulation + taper)*

E-SASE option was modeled with poor performance (bad contrast ratio, current spike too short in comparison to slippage)

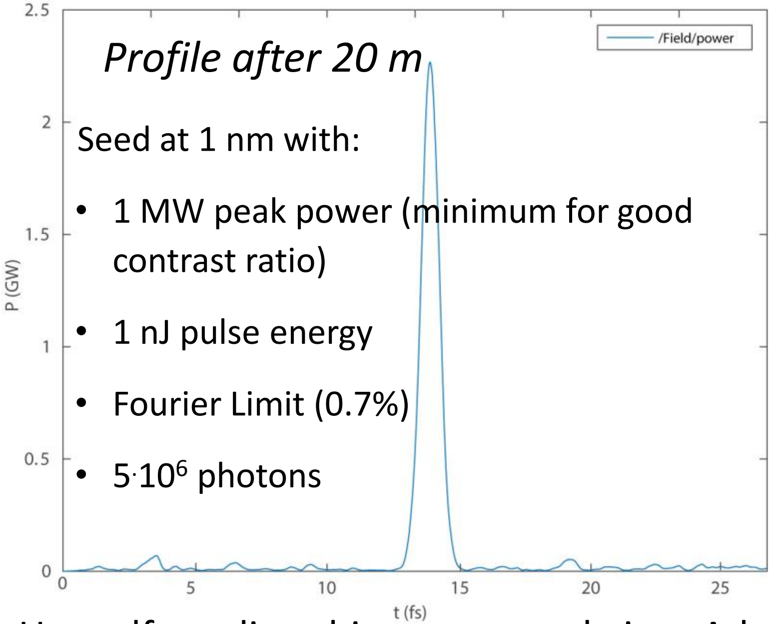
Requires the pump laser close to the undulator entrance for similar path lengths



Time locking: HHG seeding



HHG Seed



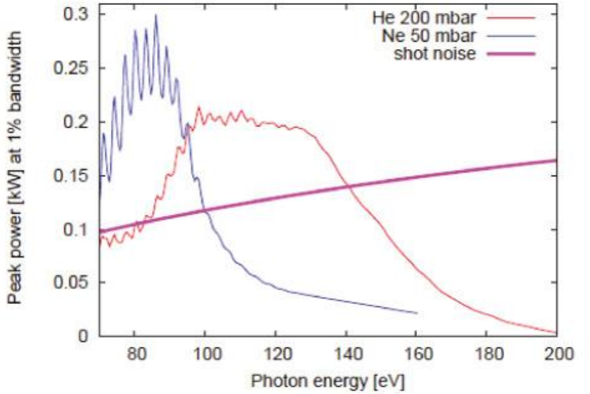
Profile after 20 m

Seed at 1 nm with:

- 1 MW peak power (minimum for good contrast ratio)
- 1 nJ pulse energy
- Fourier Limit (0.7%)
- $5 \cdot 10^6$ photons

State-of-the-Art HHG Sources

F. Ardana-Lamas et al, FEL13 (WEPSO70)



A. Ravasio et al, PRL 103, 028104 (2009)

10^9 photons @ 37 eV, 1% BW , 20 fs

M.C. Chenet al, PRL 105, 173901 (2010)

10^5 photons @ 450 eV, 1% BW , 40 fs

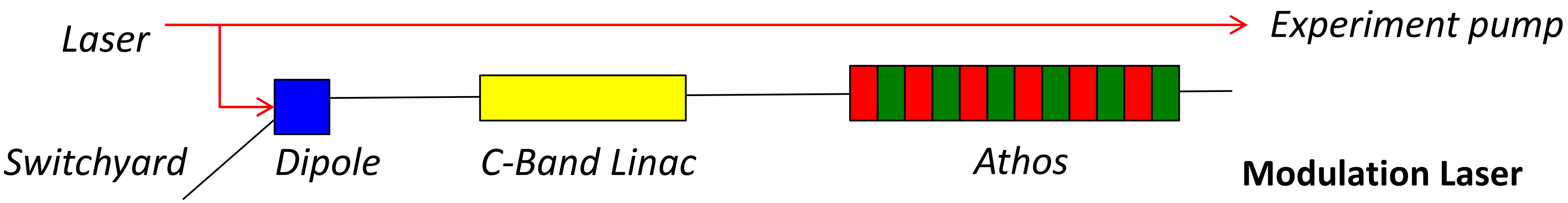
K.H. Hongal, Opt Lett 39, 3145 (2014)

$2 \cdot 10^5$ photons @ 160 eV, 1% BW , 40 fs

- Use self-seeding chicane to couple into Athos beam line
- Overlap diagnostics given by self-seeding chicane
- Possible HGHG stage from 3/4 nm → 1 nm within tuning range of undulator K-value

HHG sources need to improve by order(s) of magnitude to become feasible

Time locking: energy modulation + taper



- Possible energy modulation with last dipole of switchyard to avoid pulse lengthening by multi-period modulator
- Needs continuous taper within undulator modules to preserve resonance condition
- Not too sensitive on taper gradient. Allows for overtapering to suppress side spikes

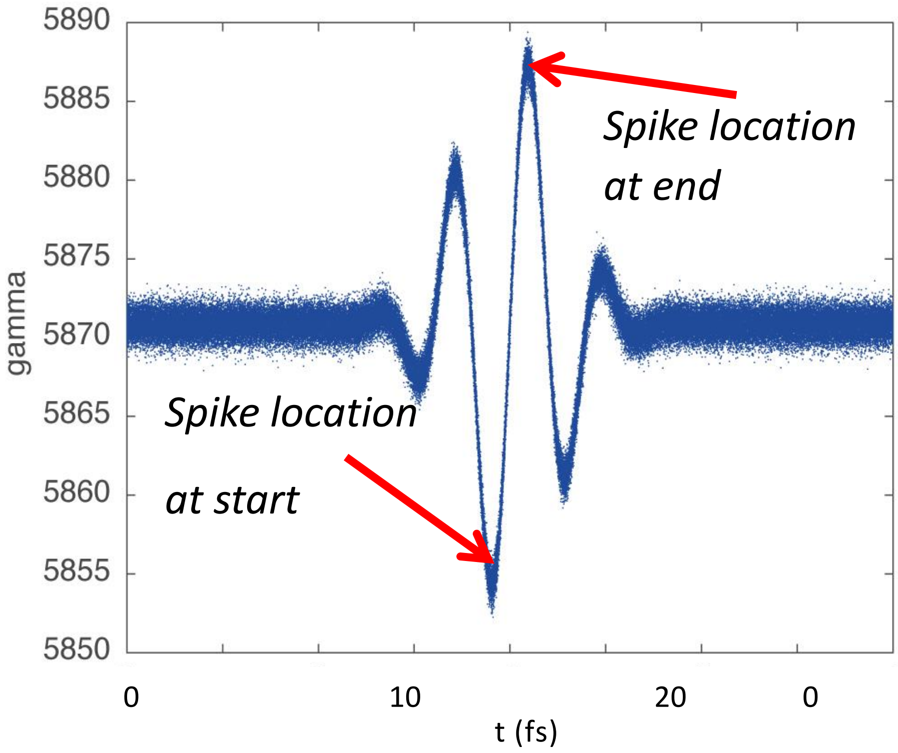
Modulation Laser

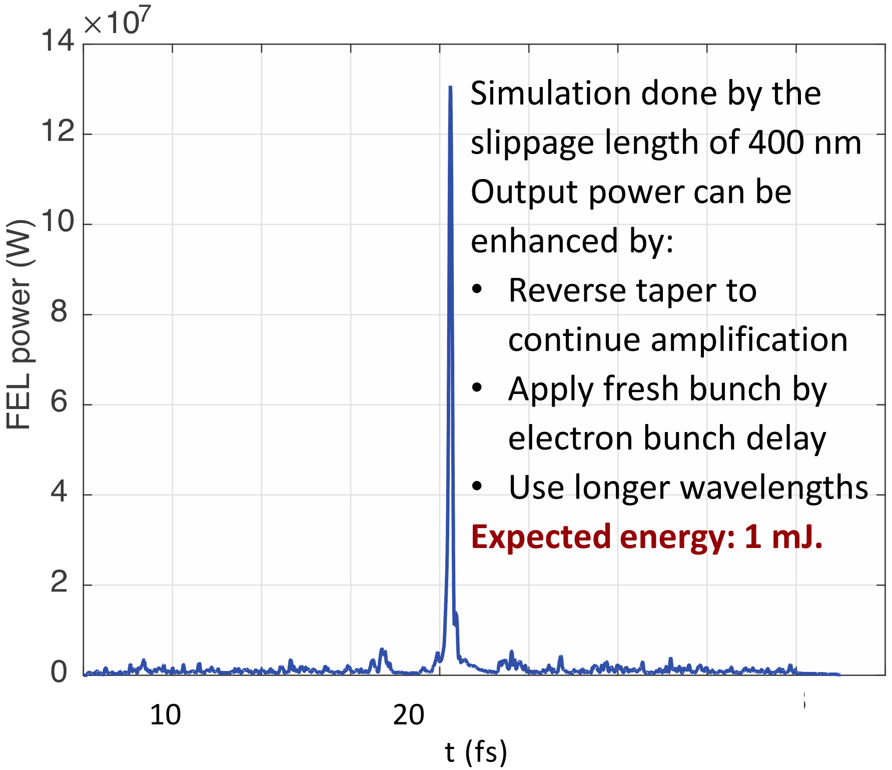
800 nm wavelength

120 mm waist size

740 GW peak power

3 fs pulse length





Simulation done by the slippage length of 400 nm

Output power can be enhanced by:

- Reverse taper to continue amplification
- Apply fresh bunch by electron bunch delay
- Use longer wavelengths

Expected energy: 1 mJ.

[E. Prat and S. Reiche, FEL15 (TUP019)]