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:: Paul Scherrer Institut

Overview of future external seeding plans at SwissFEL

FUSEE workshop, Trieste 10-11.12.2019

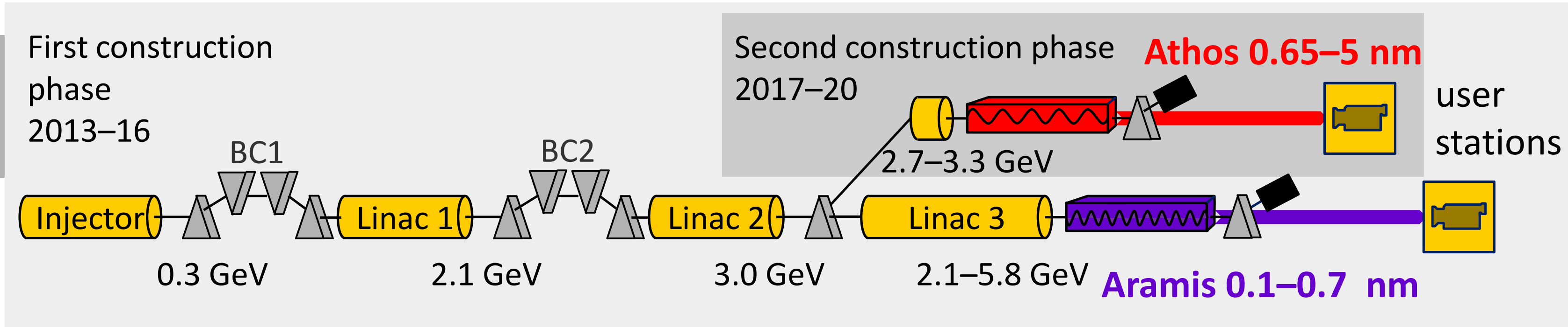
SwissFEL Overview

Athos:

Soft X-ray FEL, λ=0.65–5.0 nm

Variable polarization, Apple-X undulators

First users 2021



Aramis:

Hard X-ray FEL, λ=0.1–0.7 nm

Linear polarization, variable gap, in-vacuum undulators

First users 2018

Main parameters:

Photon wavelength: 0.1–5 nm

Photon energy : 0.2–12.4 keV

Pulse duration : 1–20 fs

Electron energy : up to 6 GeV

Electron bunch charge: 10–200 pC

Repetition rate: 100 Hz (2-bunches)

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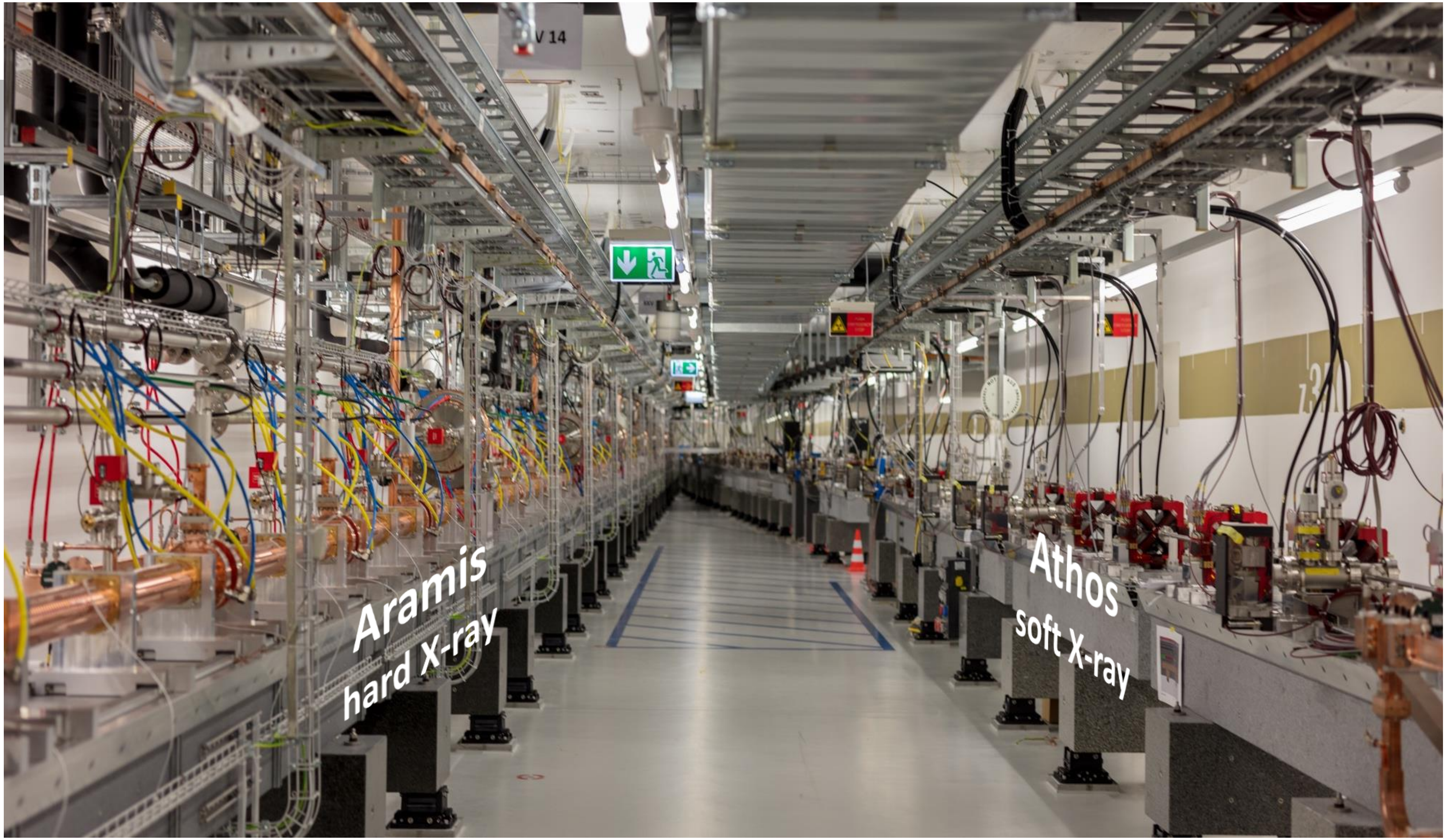
SwissFEL Overview: Aramis and Athos



SwissFEL Overview: Experimental Areas

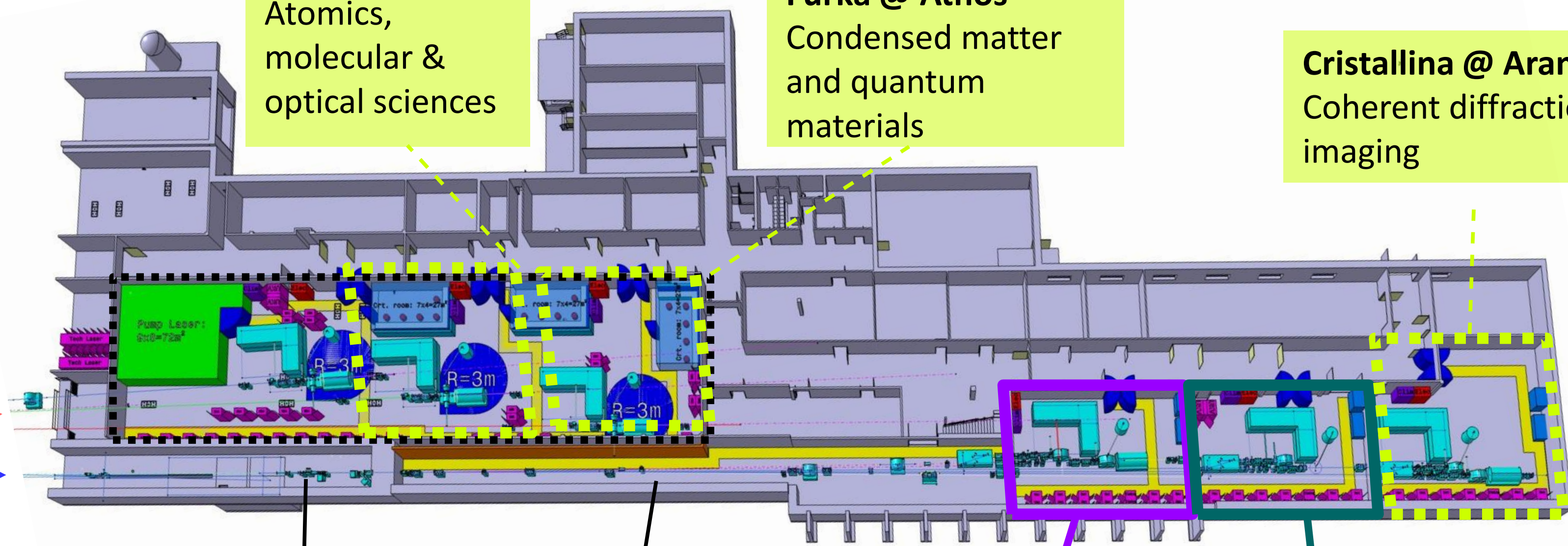
Maloja @ Athos
Atomics, molecular & optical sciences

Furka @ Athos
Condensed matter and quantum materials

Cristallina @ Aramis
Coherent diffraction imaging

(Athos FEL)

Aramis FEL



Aramis front end

Aramis optical hutch

Alvra @ Aramis
- Multipurpose pump-probe
- Ultrafast biology and chemistry

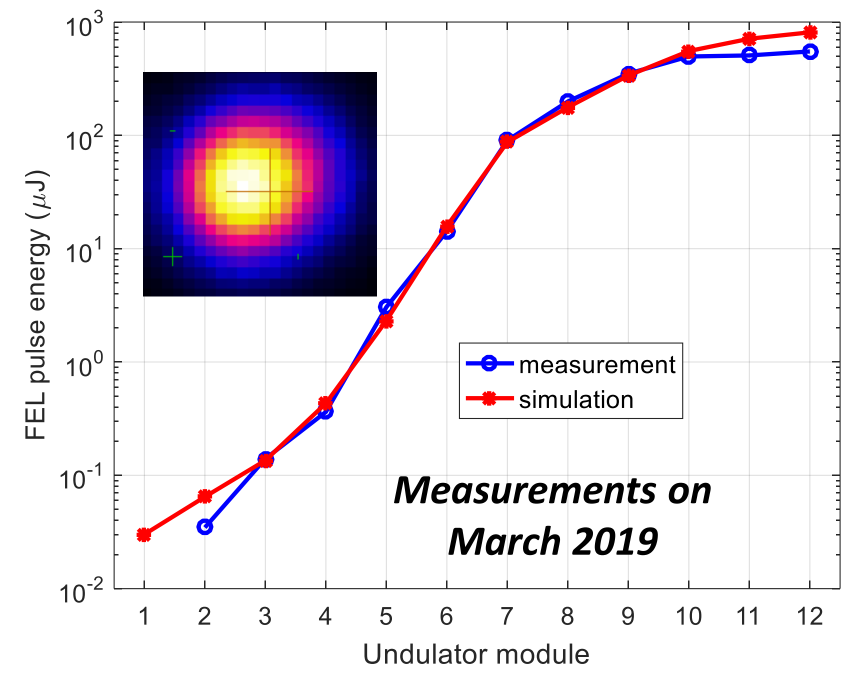
Bernina @ Aramis
- Pump-probe crystallography
- Ultrafast dynamics in solid matter, strongly correlated systems
- Structural biology (MX – macromolecuar crystallography)

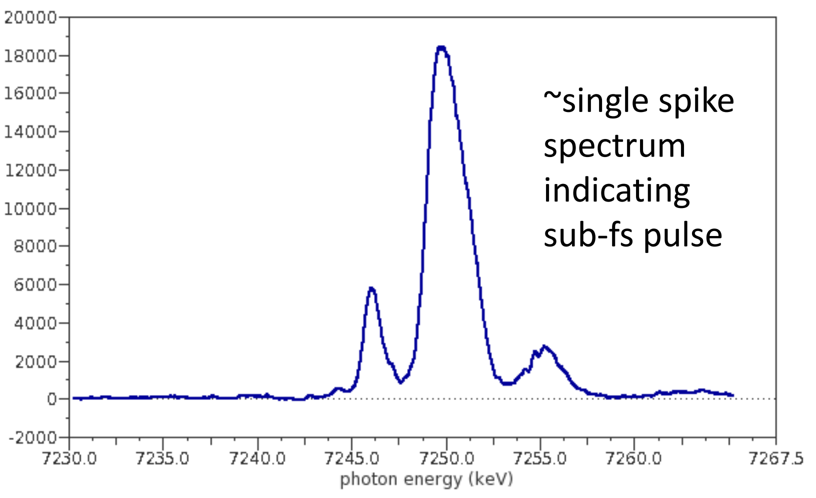
Alvra and Bernina
- Pilot experiments in 2018
- Regular user operation since January 2019

Athos stations: first users in 2021
Cristallina @ Aramis: first users in 2022

Aramis: FEL Performance

- Pulse energy: routinely few hundred µJ .
  Best: 600 µJ @ 0.1 nm (> CDR design = 150 µJ)
- Pulse duration typically 20-30 fs (RMS). Working on ultra-short pulse generation.
- Bandwidth control from ~0.15% to ~1%
- Frequency. Presently: 50 Hz. Demonstrated: 100 Hz.
- Excellent short-term stability: ~1e-4 energy jitter, ~10 fs timing jitter.
- Gain length for best performance is 2.3m, fitting simulations





Outlook

- Improve FEL performance: higher pulse energy after advanced commissioning (e.g. undulator BBA)
- Improve long-term stability
- Develop new modes:
  - Ultra-short pulse
  - 2 color pulses with adjustable delay

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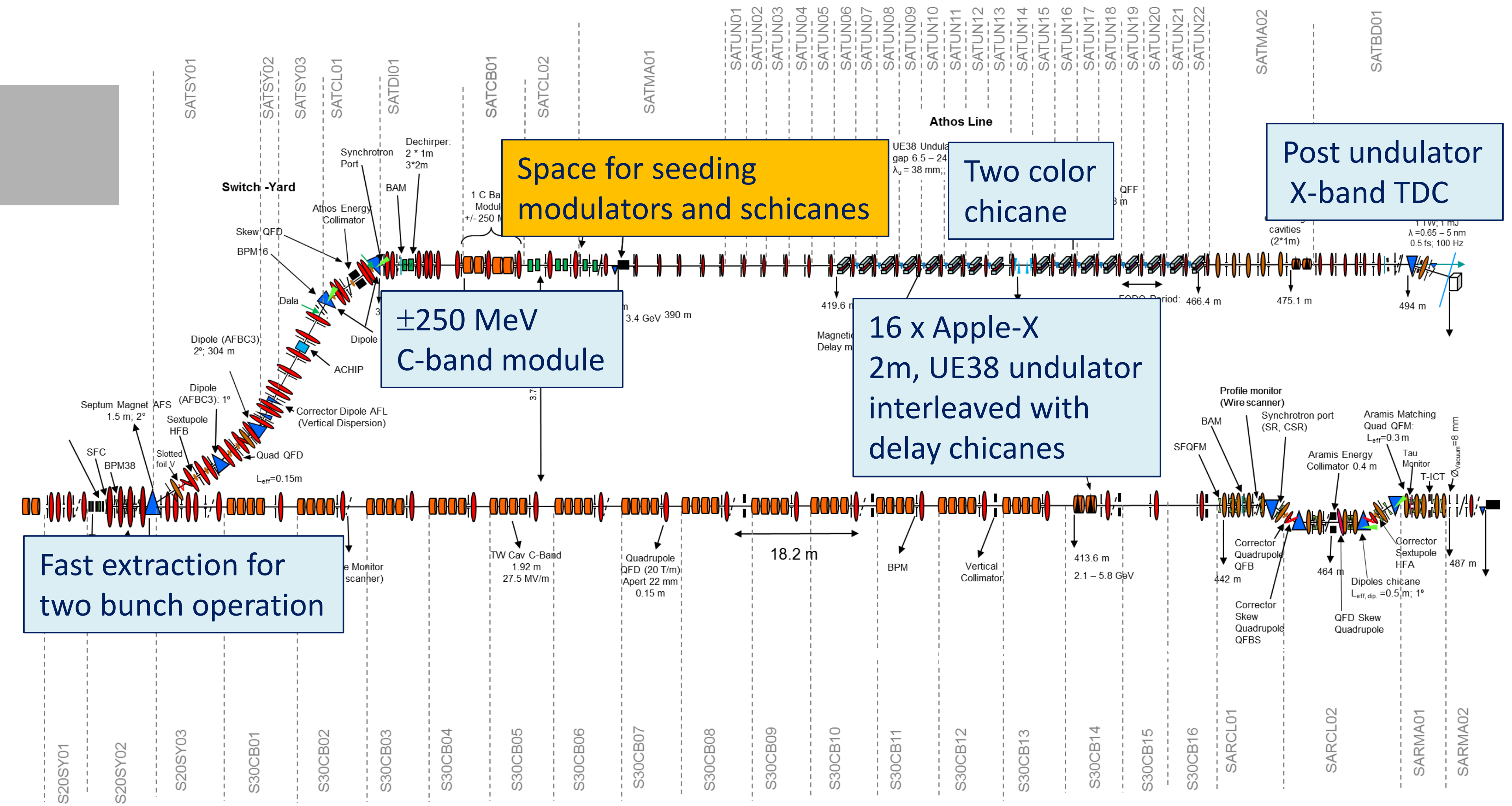
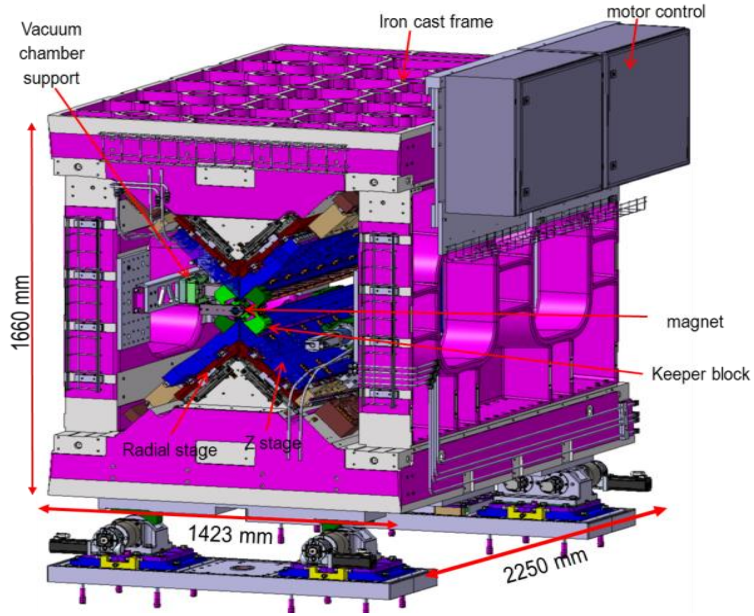
Athos beamline



Athos (Soft-X-ray Beamline)

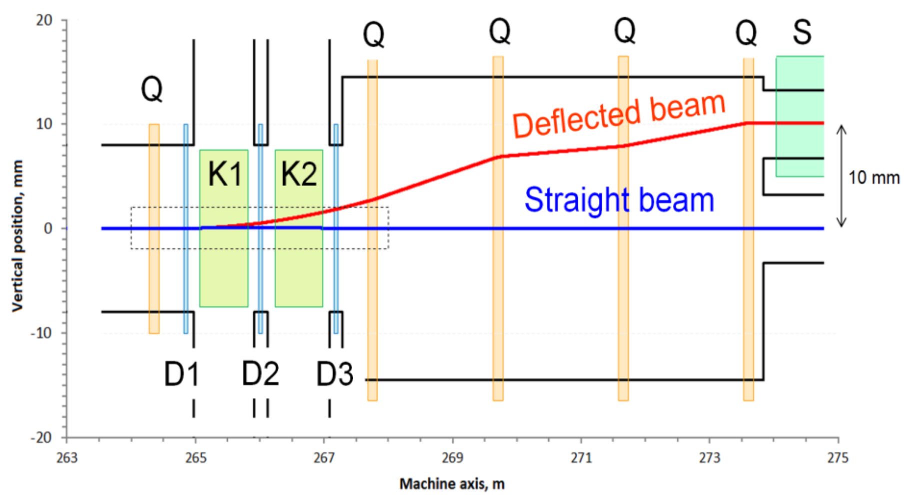


Athos U38 undulator concept

- 16 **Apple-X U38** undulators (originally 20 planned):
  - full polarization control
  - independent control on K, polarization and transverse-gradient (TGU)
- Small **interundulator magnetic chicanes** to enable
  - Optical klystron mode
  - High-brightness SASE
  - High-power and short pulses
- One large **magnetic chicane** for two-color operation (delay between –10 fs and +500 fs)

Other key components (besides undulator line)

- Custom-designed resonant kicker magnet to distribute bunches separated by 28 ns (installed and successfully tested)
- Passive dechirper (installation in 2019/2020)
- X-band TDC to diagnose electron and photon beam (ready by July 2020)



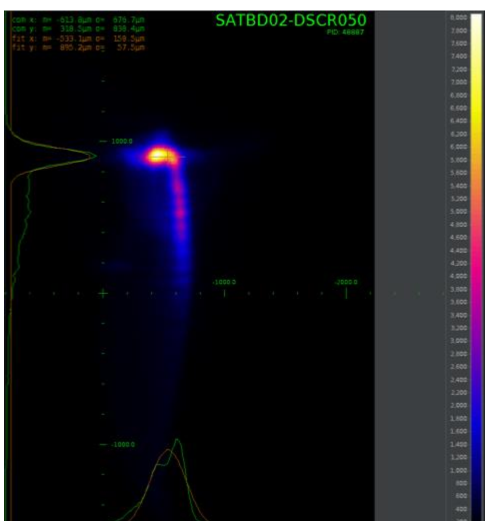
Athos Schedule

Present Vacuum system completed
2 out of 16 Apple X undulator segments installed
First beam commissioning just started (see below)
2 bunch operation with independent rep. rates for ARAMIS and ATHOS established

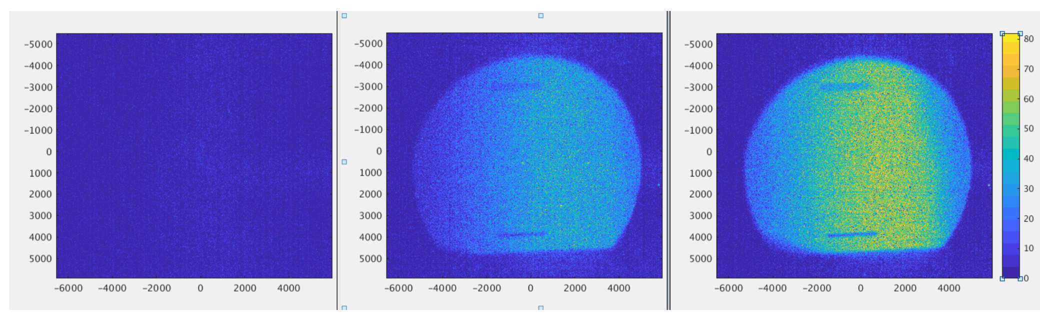
2020 Gradual installation of all undulator segments during service days
Commissioning of ATHOS FEL and photon beamlines simultaneous with ARAMIS operation
First beam on endstations
Post-undulator X-band deflector for longitudinal phase space diagnostic

2021 First users
Installation of HERO

December 2nd 2019,
first beam on ATHOS beam dump

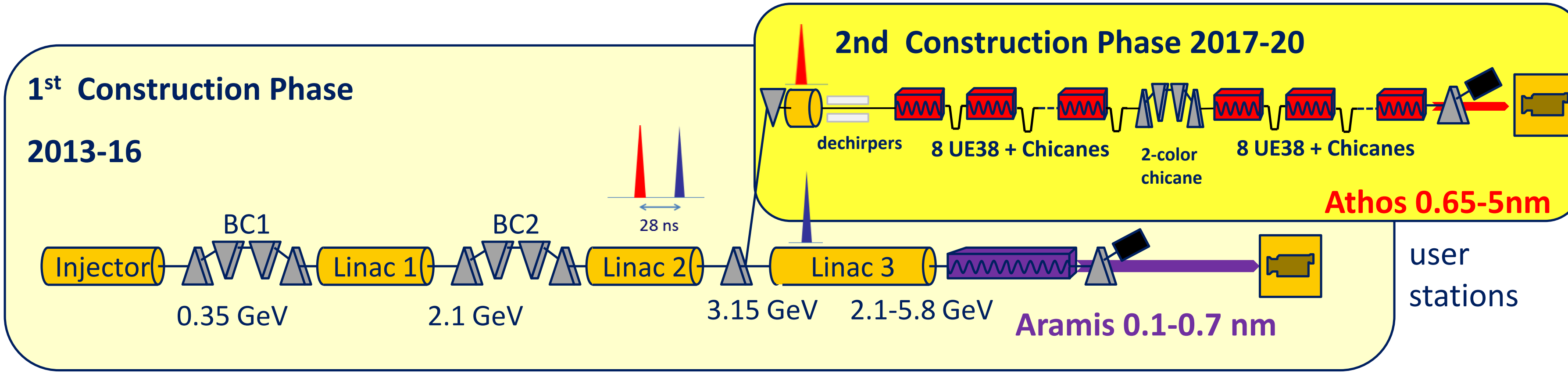


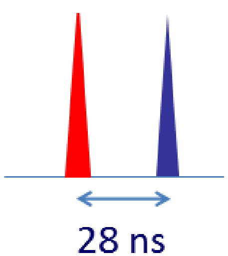
December 3rd 2019
First spontaneous undulator radiation from Apple X



all segments open / one segment closed / two segments closed

Two bunch operation





Two gun lasers:

Jaguar / Mizar

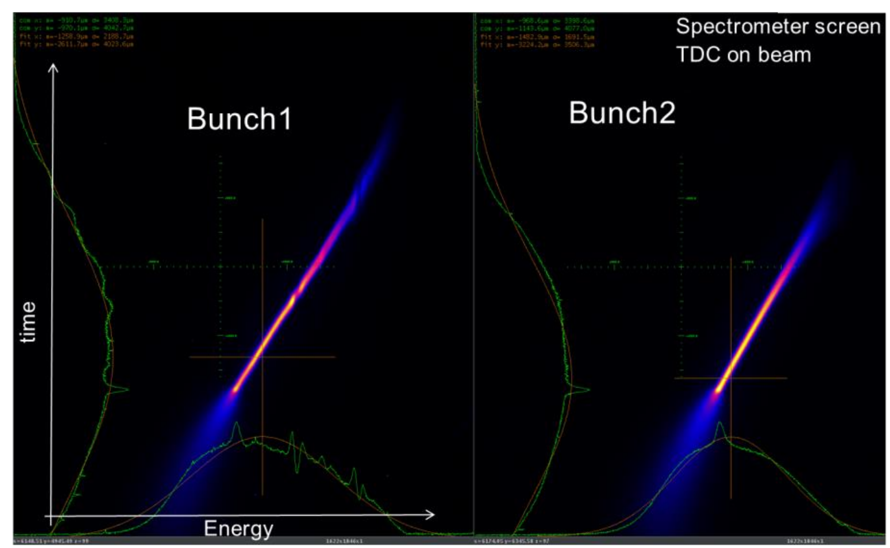
Alcor

Fast kicker + DC septum

Two separate ARAMIS

and ATHOS bunches

Two-bunch transport in the same RF macropulse !



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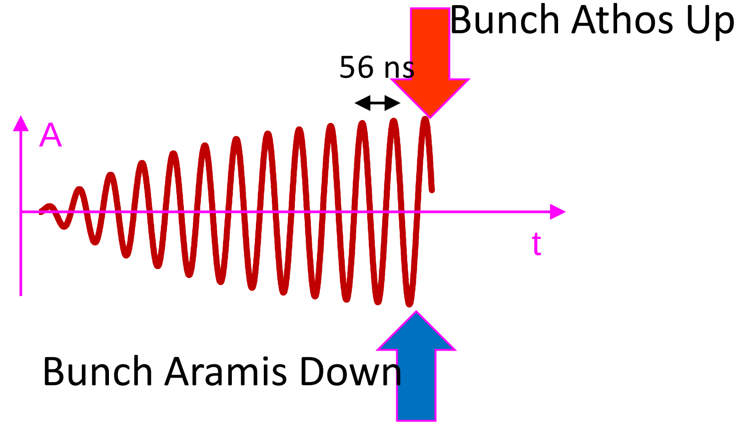
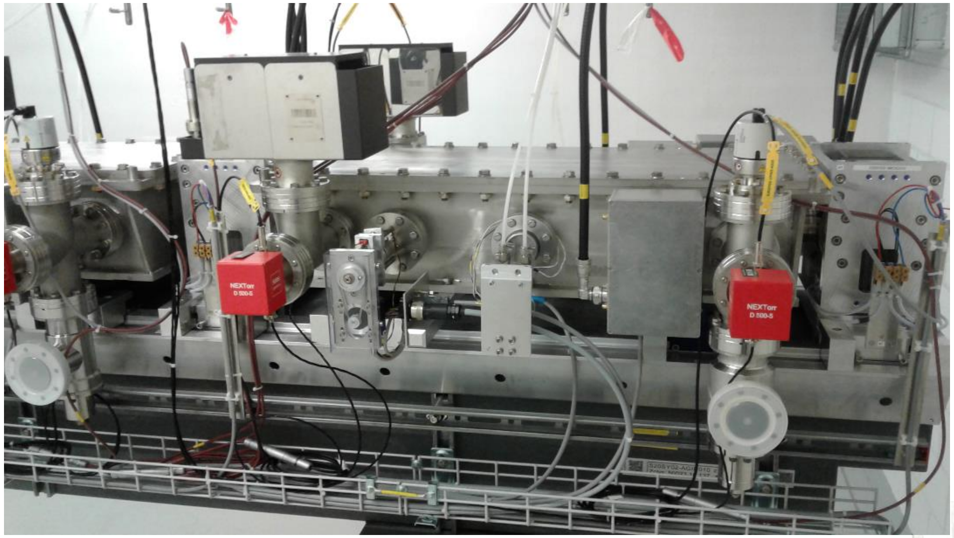
Fast kickers & Septum

Fast kicker kicks both bunches !

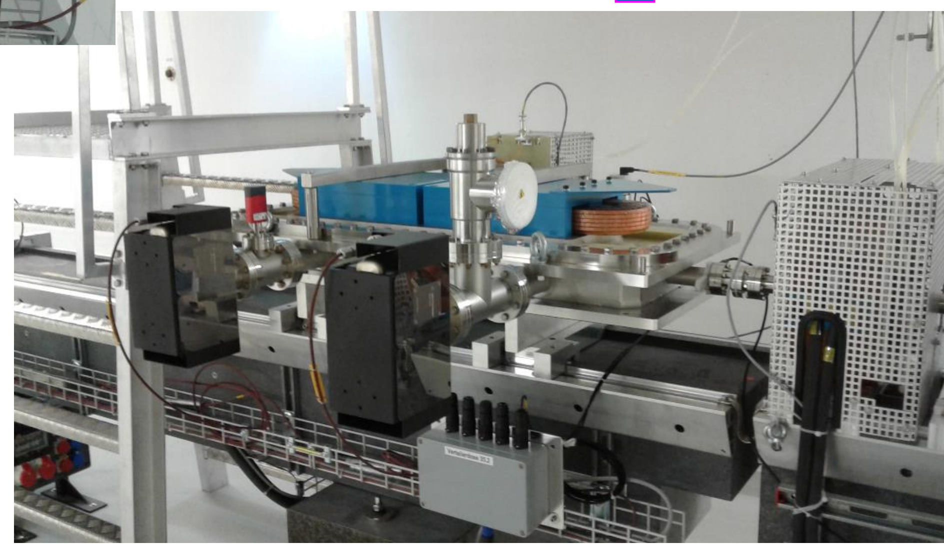




Beam energy: 3.1 GeV

Kicker amplitude stability (pulse to pulse): 3.10^{-6} rms

What beam orbit stability after fast kicker?

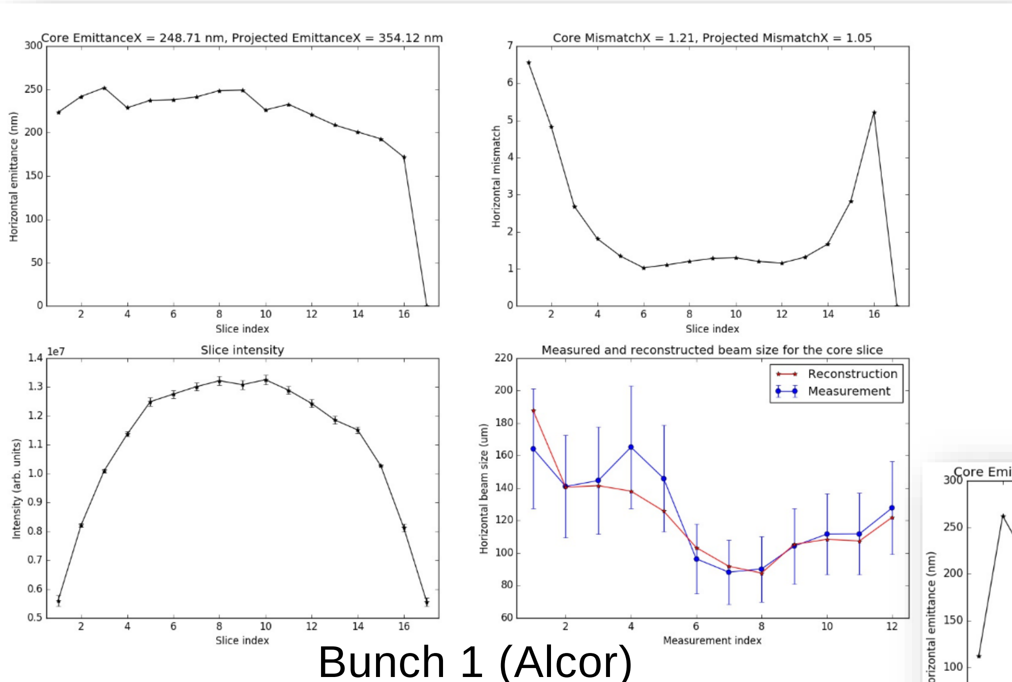


Courtesy of M. Paraliev

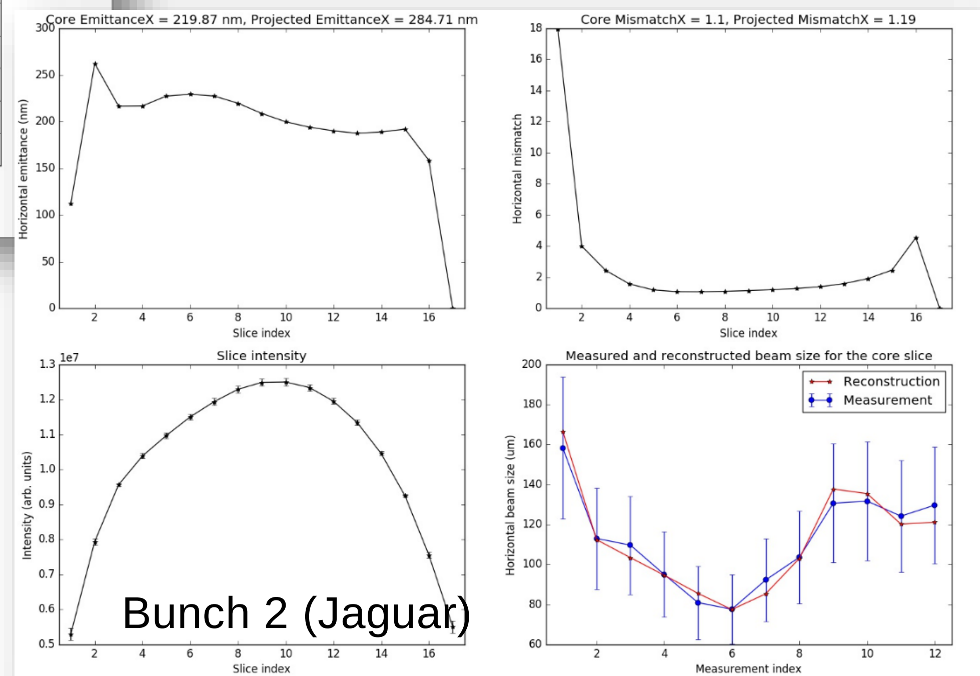
Septum deflects beam at Y=10mm (0.384 T.m at 105.6A)

Slice emittance comparison after compression

Bunch 1 (Alcor): $\varepsilon_{x,slice}$= 250 nm
Bunch 2 (Jaguar): $\varepsilon_{x,slice}$=220 nm
difference: 10-15 %



Bunch 1 (Alcor)



Bunch 2 (Jaguar)

Emittances good for lasing

for both bunches!

Courtesy of E. Prat

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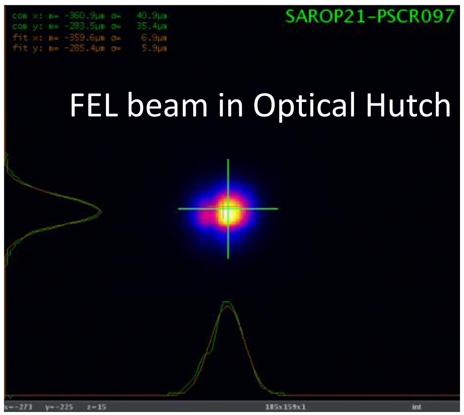
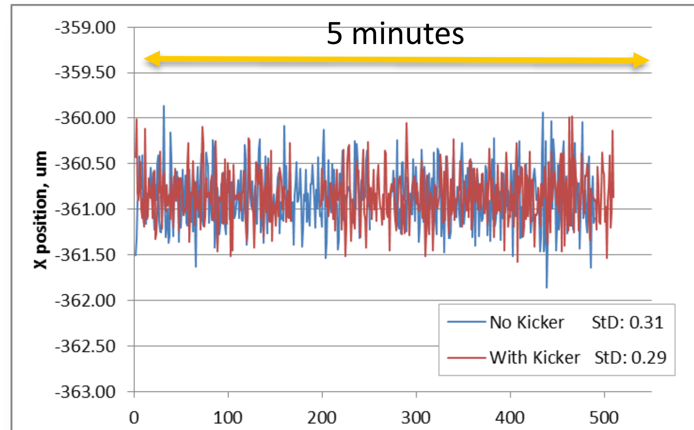
Aramis FEL pointing stability with fast kickers

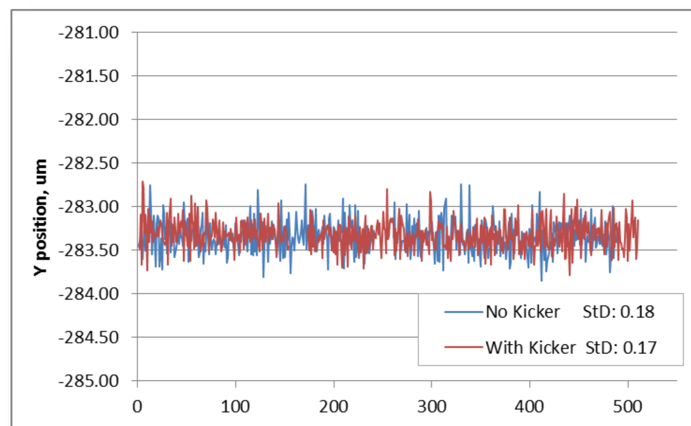


Beam Shift – 11.10.2018



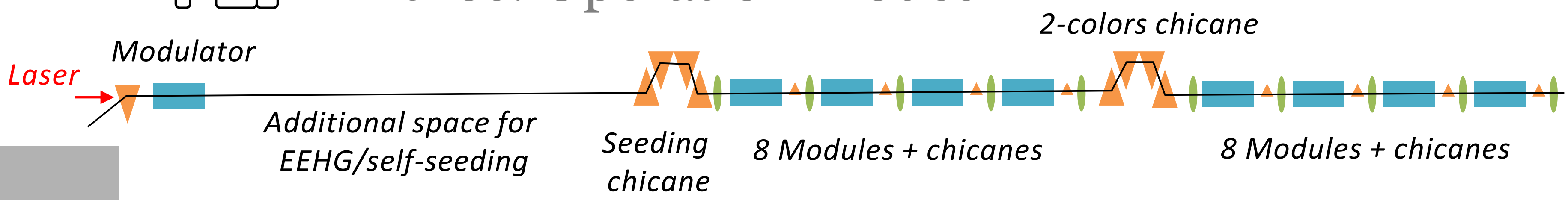
Horizontal beam position with / without kickers:
0.29 / 0.31 µm rms

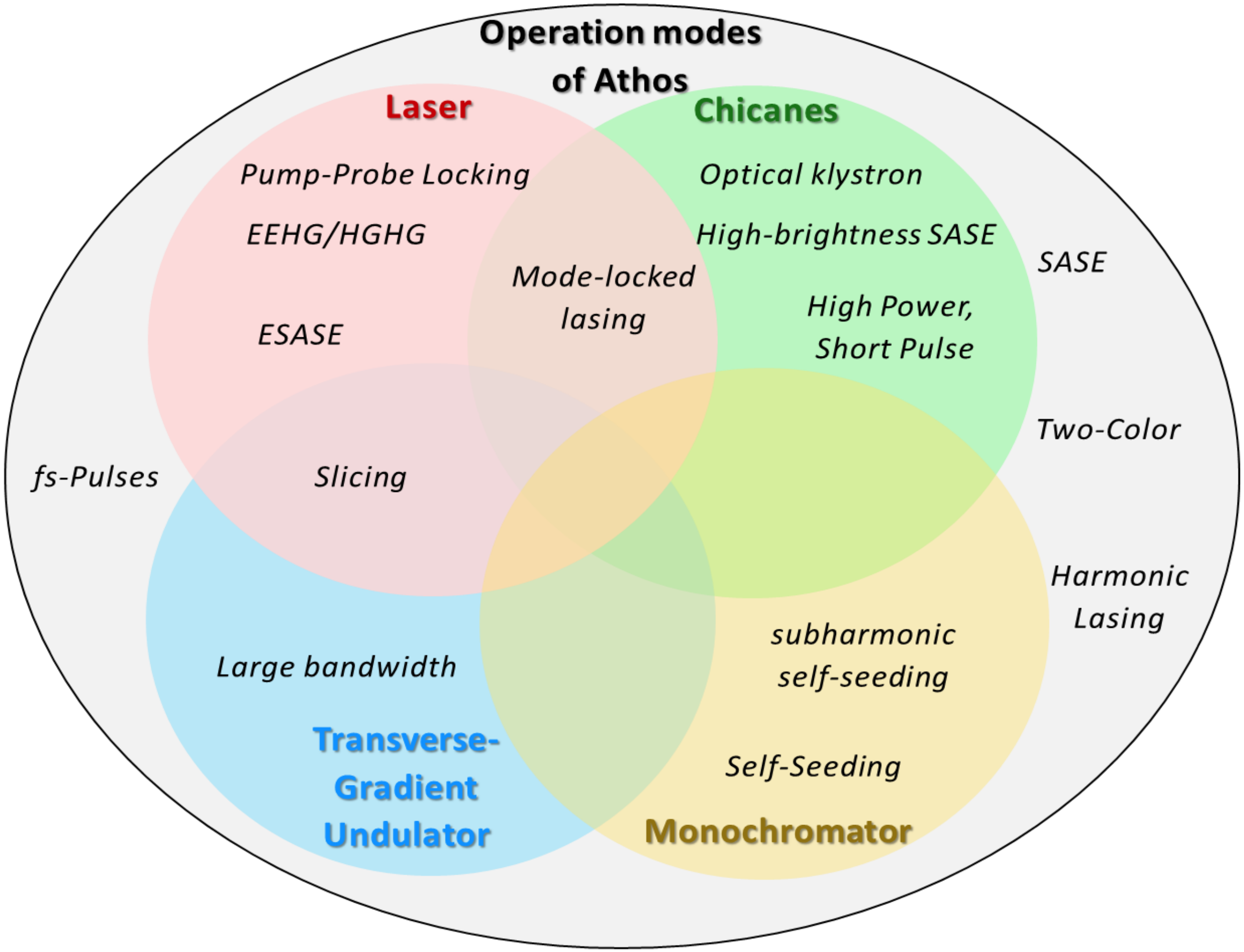
No influence of kicker on FEL pointing stability !



Vertical beam position stability with / without kickers:
0.17 / 0.18 µm rms

Athos: Operation Modes





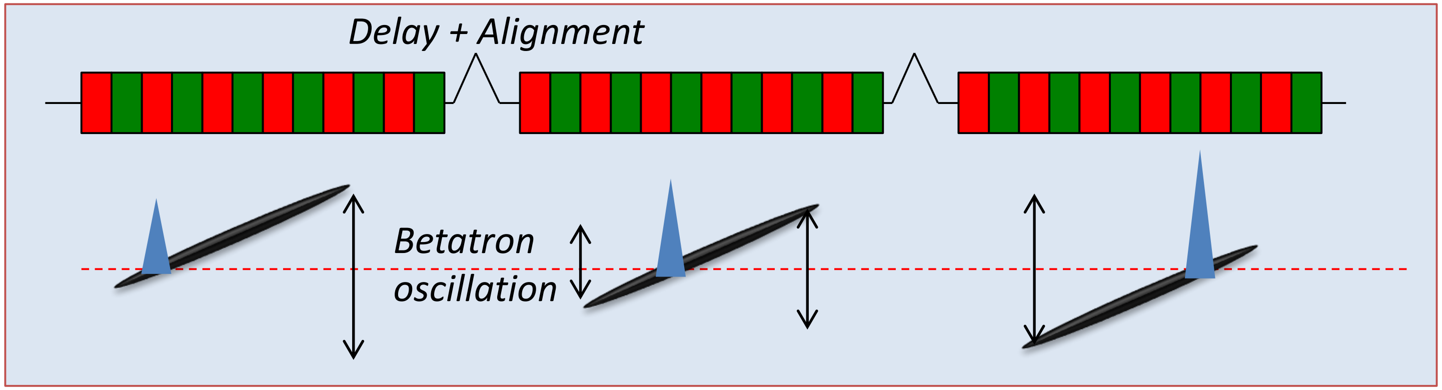
Many operation modes, some of them unique.
Main hardware:

- Inter-undulator chicanes
- TGU
- Laser
- Monochromator (not baseline)

Few examples in the next slides

Generation of High-Power and Short Pulses

- Shift the FEL pulse to fresh electrons for “superradiant” amplification (with chicanes)
- The fresh bunch slices are derived from a realignment of a tilted beam



[E. Prat, F. Löhl and S. Reiche, PRSTAB 18, 100701 (2015)]

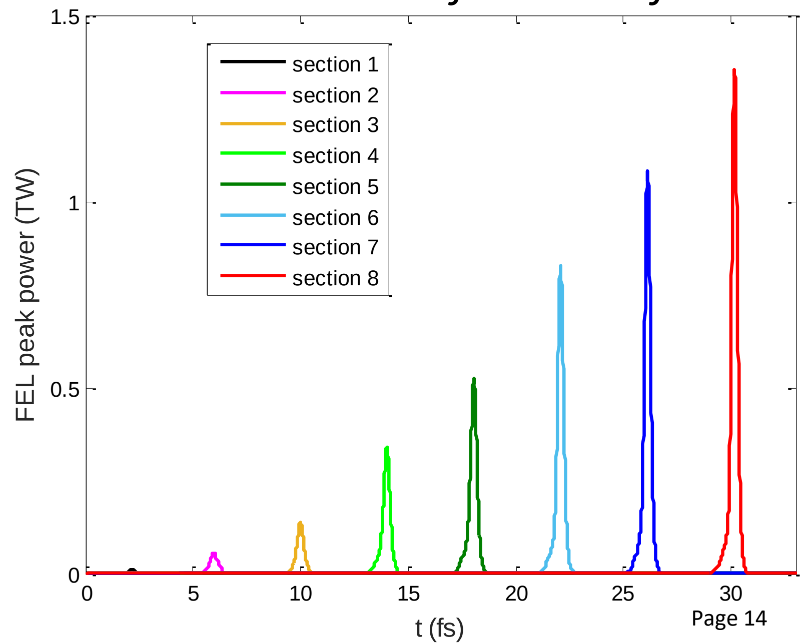
Simulation results for SwissFEL

20 modules, 2 nm, 6 kA, 8 sections

Tilt in offset (mm)	Peak power (TW)	Pulse energy (mJ)	FWHM pulse duration (as)
1.5	1.62±0.58	1.01±0.24	460±260
3	1.48±0.20	0.52±0.05	300±10

Demonstrated at LCLS with 3 sections *[A. Lutman et al, PRL 120, 264801, 2018]*

FEL radiation profile after each undulator section for a tilt of 3 mm



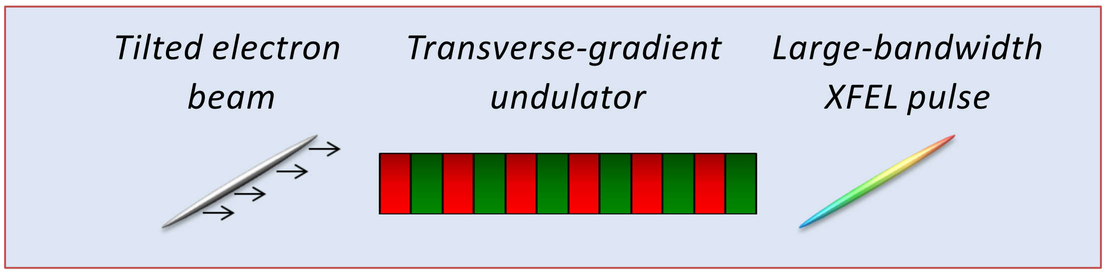
Large Bandwidth with TGU

In a TGU there is a dependence of the undulator field on the transverse position

$$\frac{K(x) - K_0}{K_0} = \alpha x$$

K_0: on-axis field
α: gradient

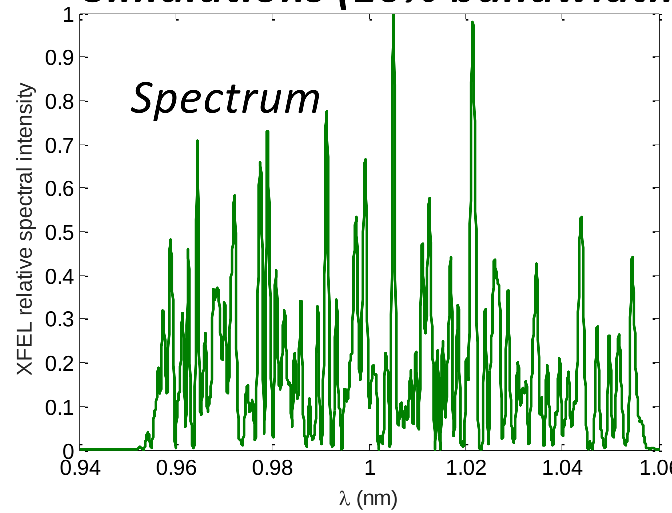
A tilted beam traveling through a TGU will produce broadband XFEL radiation. Easy to tune!

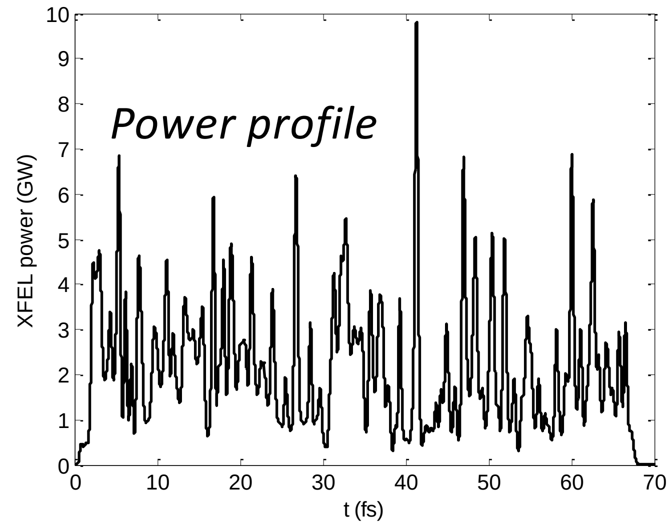


[E. Prat, M. Calvi, and S. Reiche, JSR 23, 874 (2016)]

- Additional possibilities of the scheme:
  - Multiple colors with slotted foil at the undulator entrance
  - FEL pulse compression (sign of the chirp can be controlled)

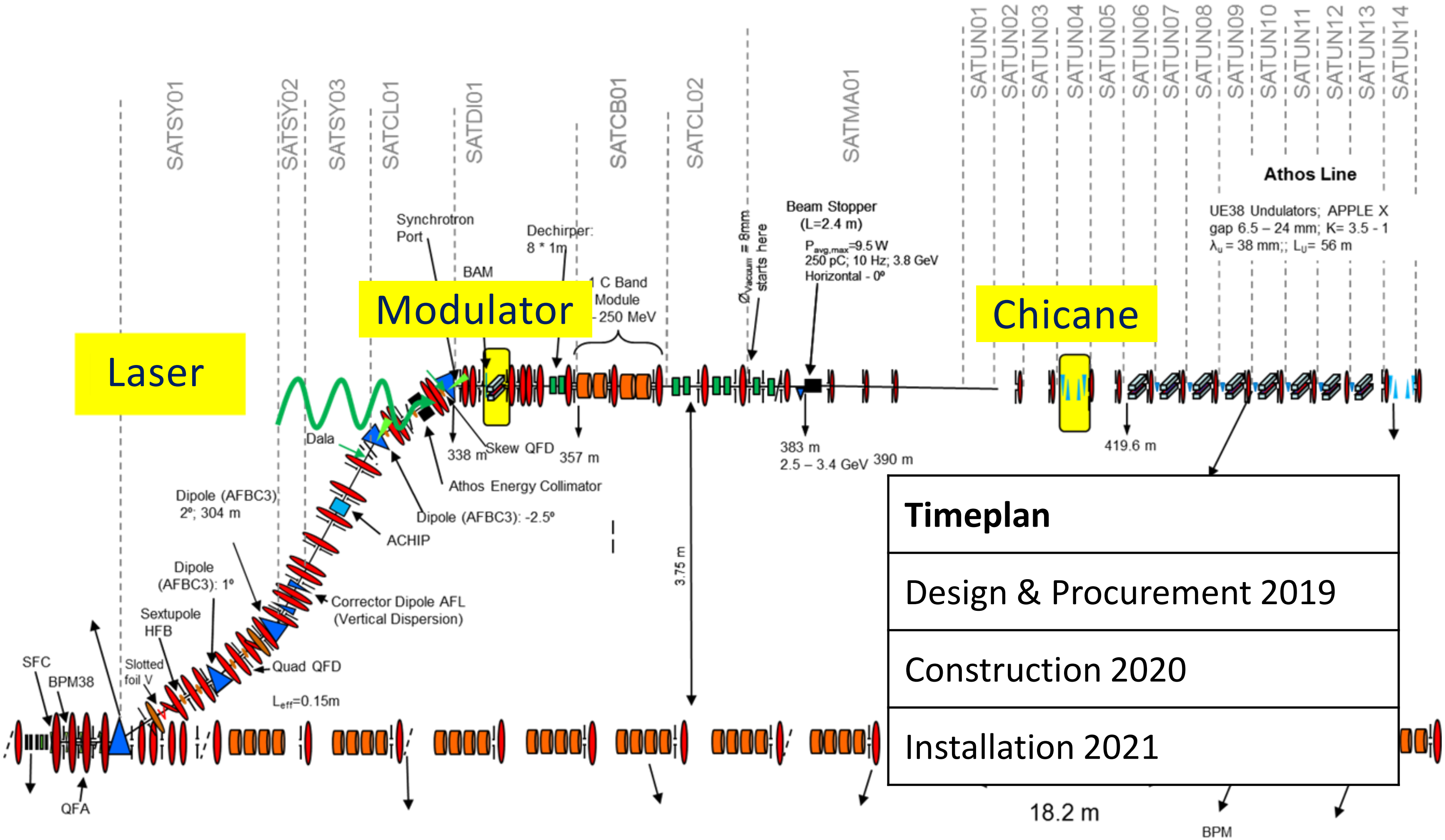
Simulations (10% bandwidth)





XFEL pulses of 20% bandwidth and few GW power can be obtained

HERO*



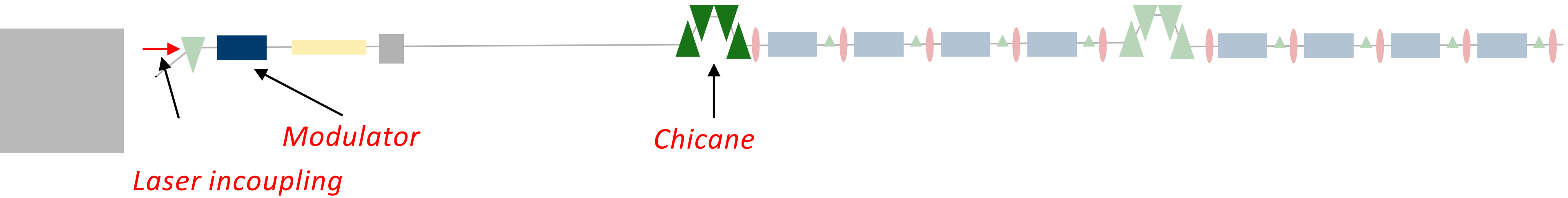
Timeplan
Design & Procurement 2019
Construction 2020
Installation 2021

Motivation: Time locking to external source; attosecond pulses

*part of ERC synergy project “Hidden, Entangled and Resonating Orders” ,
G. Aeppli, H. Rønnow, N. Spaldin and A. Balatsky

HERO Layout and Machine Side Hardware

Hardware



- Modulator (about 1.5 m)
- Chicane
  - Identical copy of the two-color chicane with an delay of up to 500 fs (max R_{56} is 300 μm)
- Vacuum chamber for SATCL01-MBND300 with Laser Incoupling
- 2 Screens (before and after modulator for overlap)
  - Electron beam, Laser beam at fundamental, 2^{nd} and 3^{rd} harmonic
- 1 BPM next to one of the screen
- 1 QFD magnets close to the exit of SATCL01-MBND300 to control beamsize in Modulator

Certain elements after SATDI01-DBCM010 needs to be redistributed to fit in modulator.

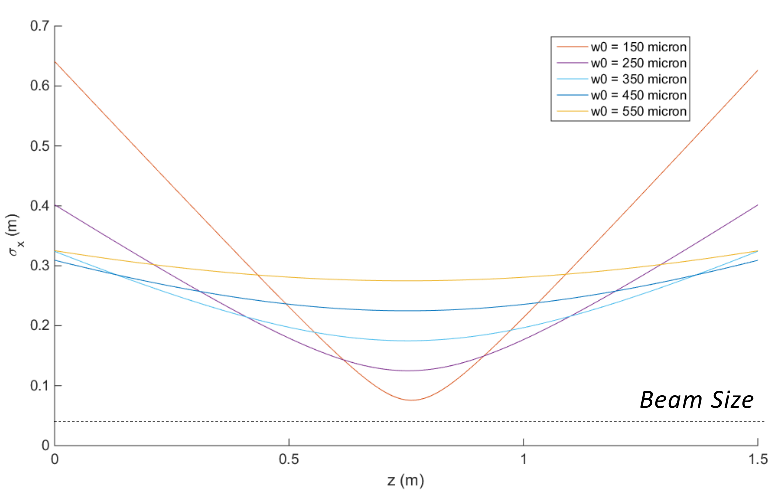
Modulator

- Optimized for resonance between 266 to 800 nm
- Crude definition (needs feedback from ID group):
  - Period Length about 25 cm, 6 periods, maximum K ~ 25
  - Shorter period, higher K would be even better.
  - 800 nm → K = 22.3, 266 nm → K = 9.1

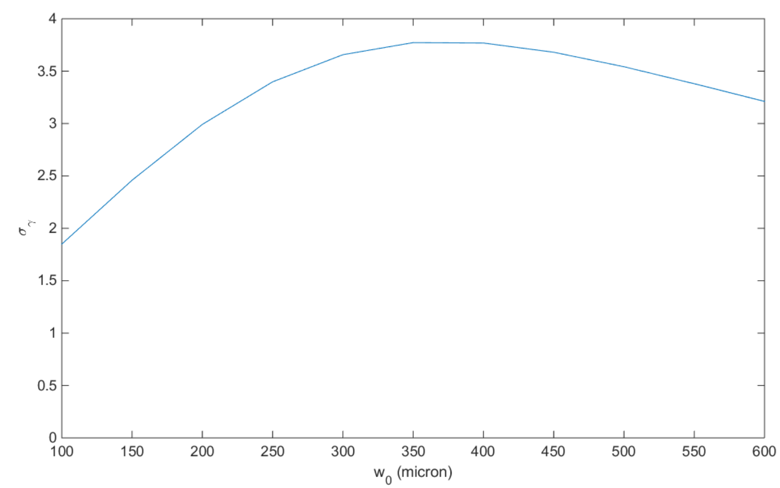
Energy Scaling

$$\frac{\Delta\gamma}{\gamma} \propto \frac{EK}{\gamma} L_M$$

RMS beam size in x within Modulator @ 800 nm



Modulation efficiency

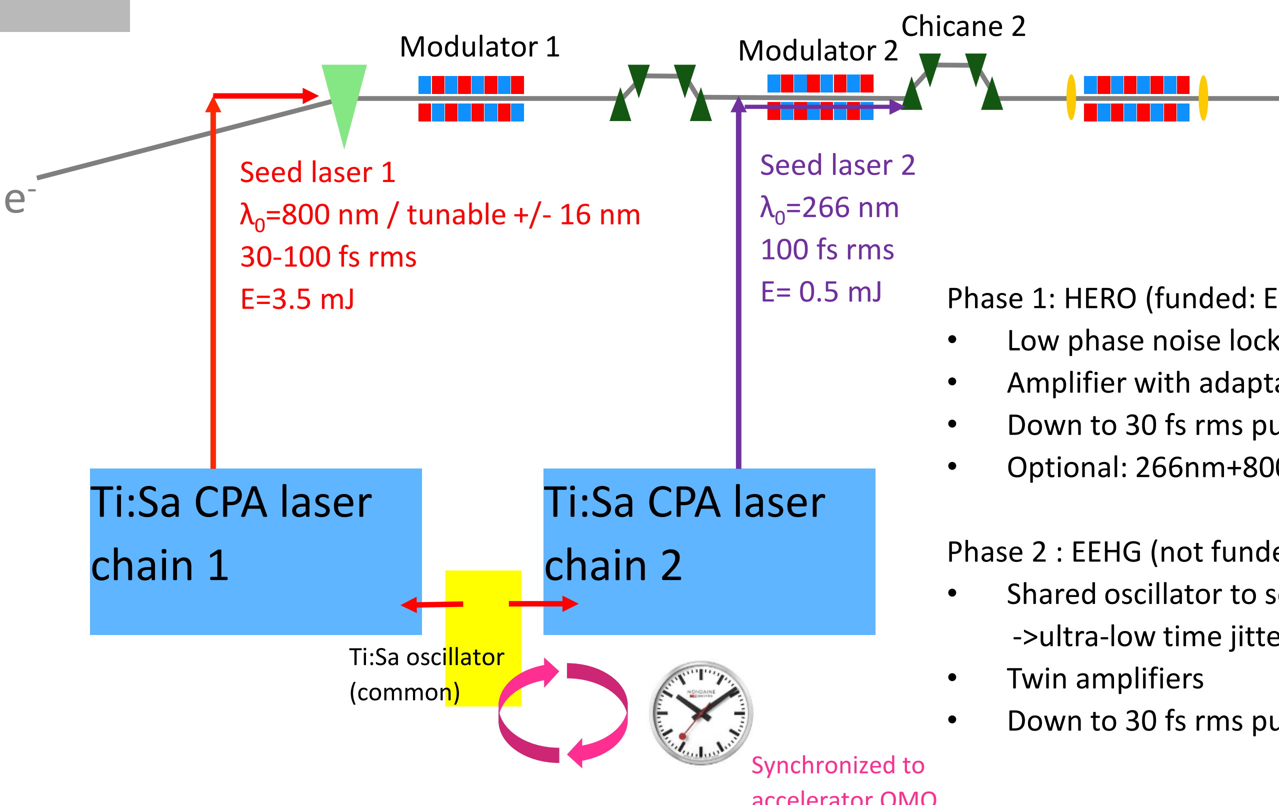


Best energy transfer at 800 nm for w_0=350 micron → z_R = 50 cm

Laser – Additional Requirements

- Central wavelength of 800 nm but transport and incoupling should support fundamental, 2nd and 3rd harmonics.
- Maximum pulse length of 100 fs RMS to guarantee "easier" overlap with electron beam, though shorter pulses (down to 10 fs) are also beneficial
- "Coarse" longitudinal overlap (<~50 ps-level) achieved with OTR foil and photodiode + oscilloscope (screen position after the modulator, no COTR suppression geometry).
- Overlap achieved with BPM/Screen combos before and after modulator and longitudinal phase-space measurement with X-band TDS. E-beam feedback signals to preserve overlap are the BPMs and the BAM next to the modulator.

SwissFEL laser system for HERO and EEHG



Phase 1: HERO (funded: ERC grant from G. Aeppli)

- Low phase noise locked oscillator (<20 fs rms jitter)
- Amplifier with adaptative spectral filtering for wavelength tuning [1]
- Down to 30 fs rms pulse duration @ 800 nm CWL
- Optional: 266nm+800nm in modulator 1

Phase 2 : EEHG (not funded yet)

- Shared oscillator to seed amplifier 2
  ->ultra-low time jitter between laser 1 and 2
- Twin amplifiers
- Down to 30 fs rms pulse duration @ 266 CWL

[1] A. Trisorio *et. al.* Optics Express **19,** p 20128 (2011)

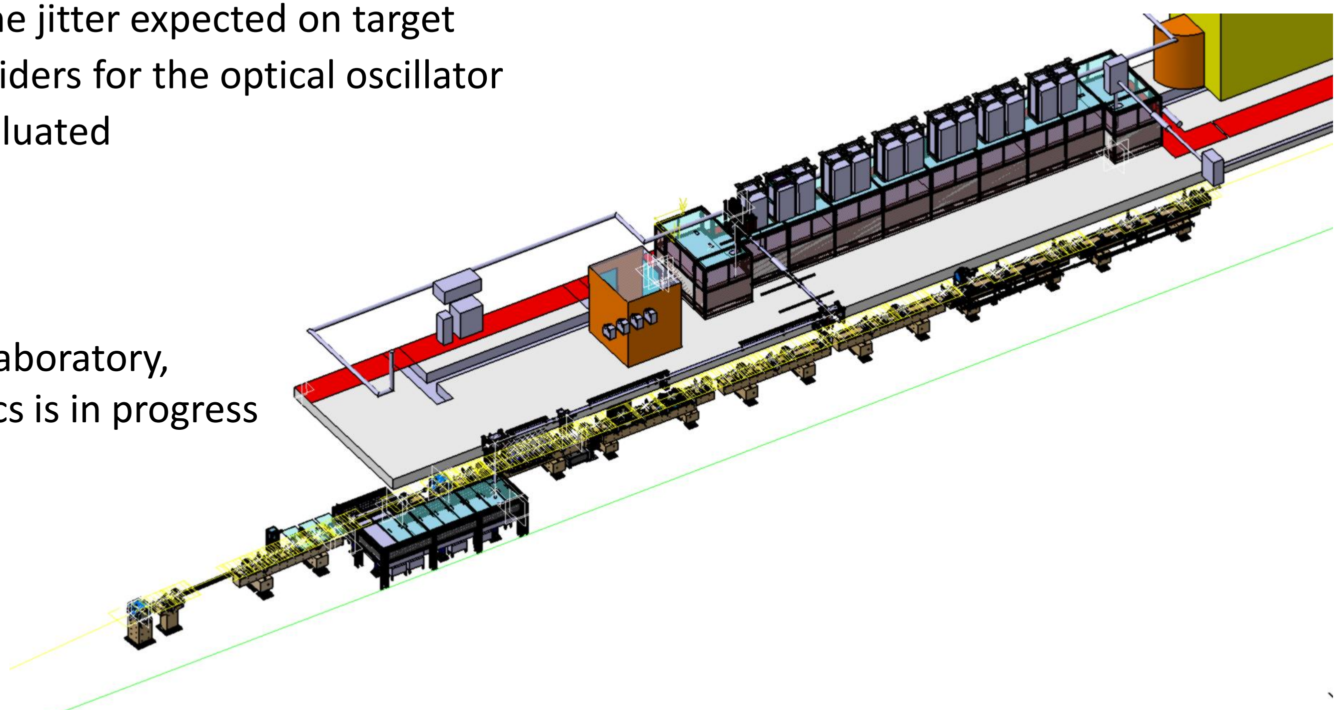
SwissFEL laser system for HERO and EEHG cont.

Laser system:

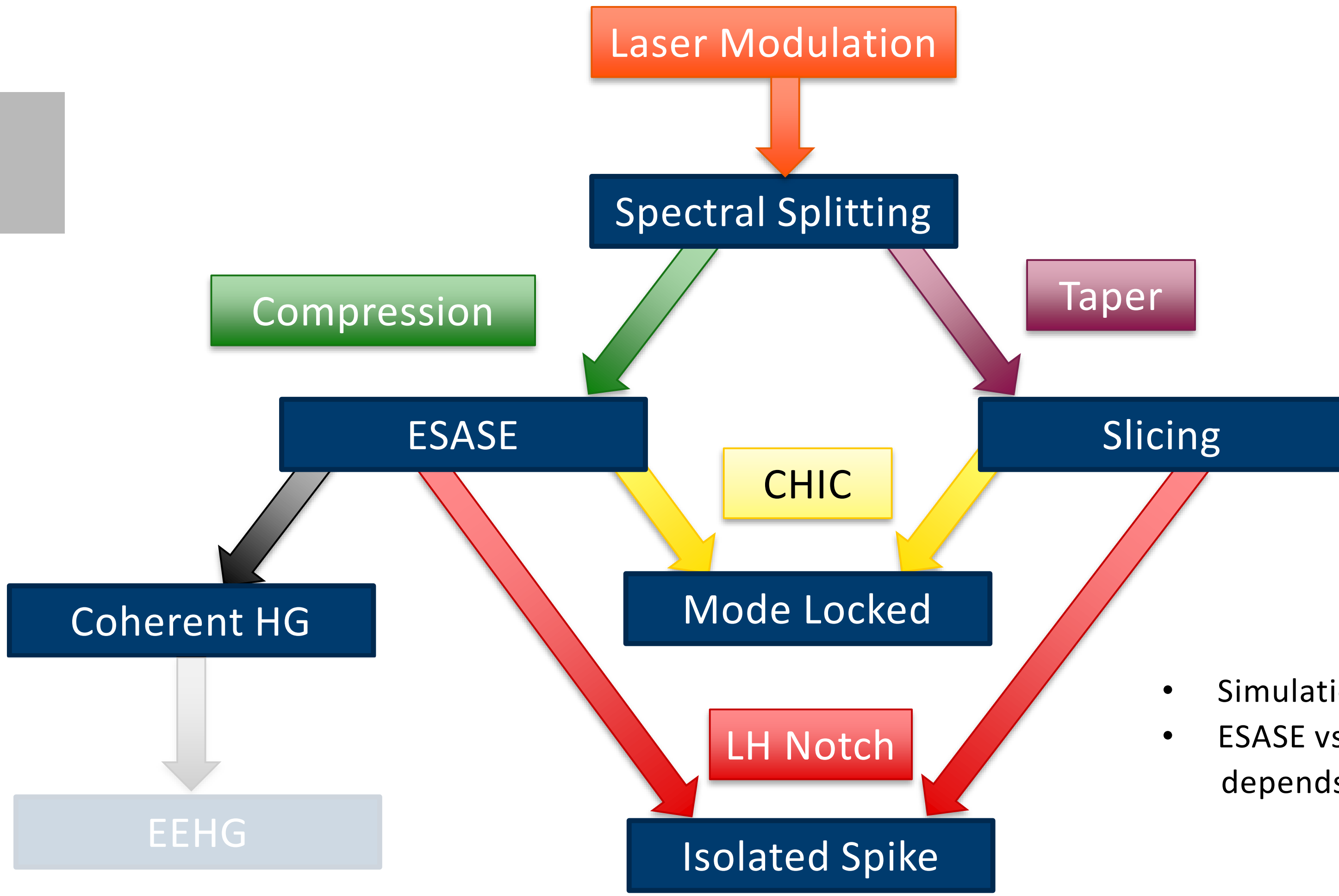
- Amplifiers 1 and 2 are existing PSI hardware, a few modifications and upgrade are required
  - ✓ Minimize laser procurement costs
  - ✓ Redundancy given by 2 twins systems
  - ✓ Low time jitter expected on target
- Possible providers for the optical oscillator are being evaluated

Infrastructure:

General 3D design of the laser laboratory, transfer line and launching optics is in progress



Operation Modes with HERO

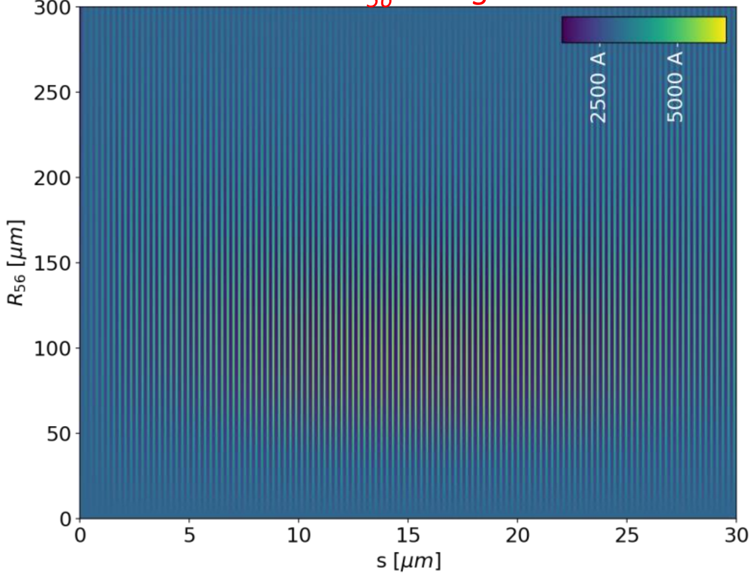


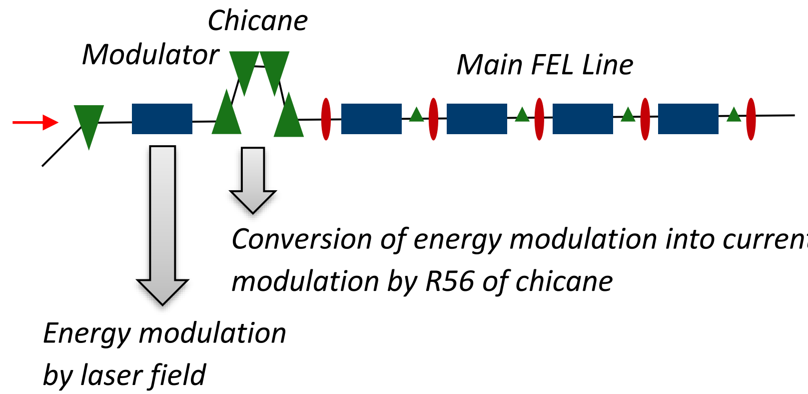
- Simulations done at 1nm
- ESASE vs Slicing performance depends on FEL wavelength

Each Mode has different specification regarding seed power and wavelength.

ESASE (“Enhanced SASE”)

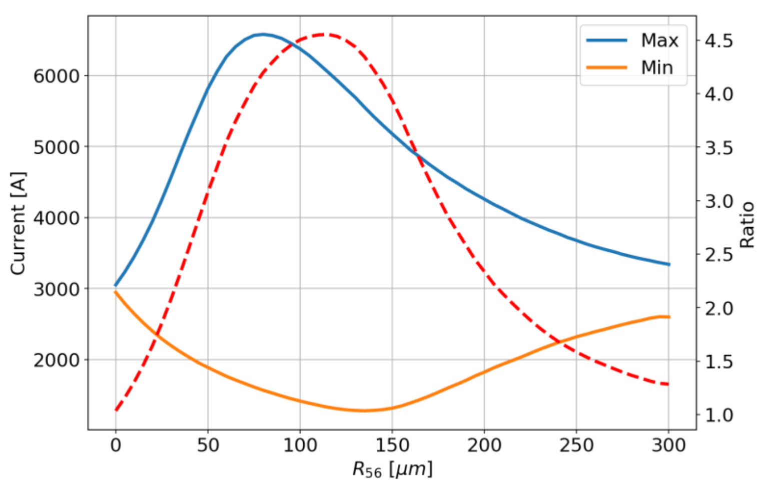
Current vs. R_{56} along the bunch



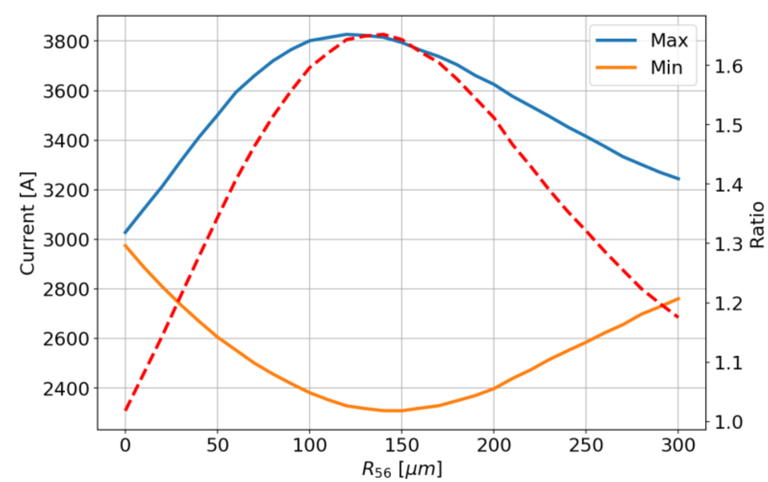


2 Parameters to Optimize

Current vs. R_{56} seed 1.5e8 W



Current vs. R_{56} seed 1.0e7 W



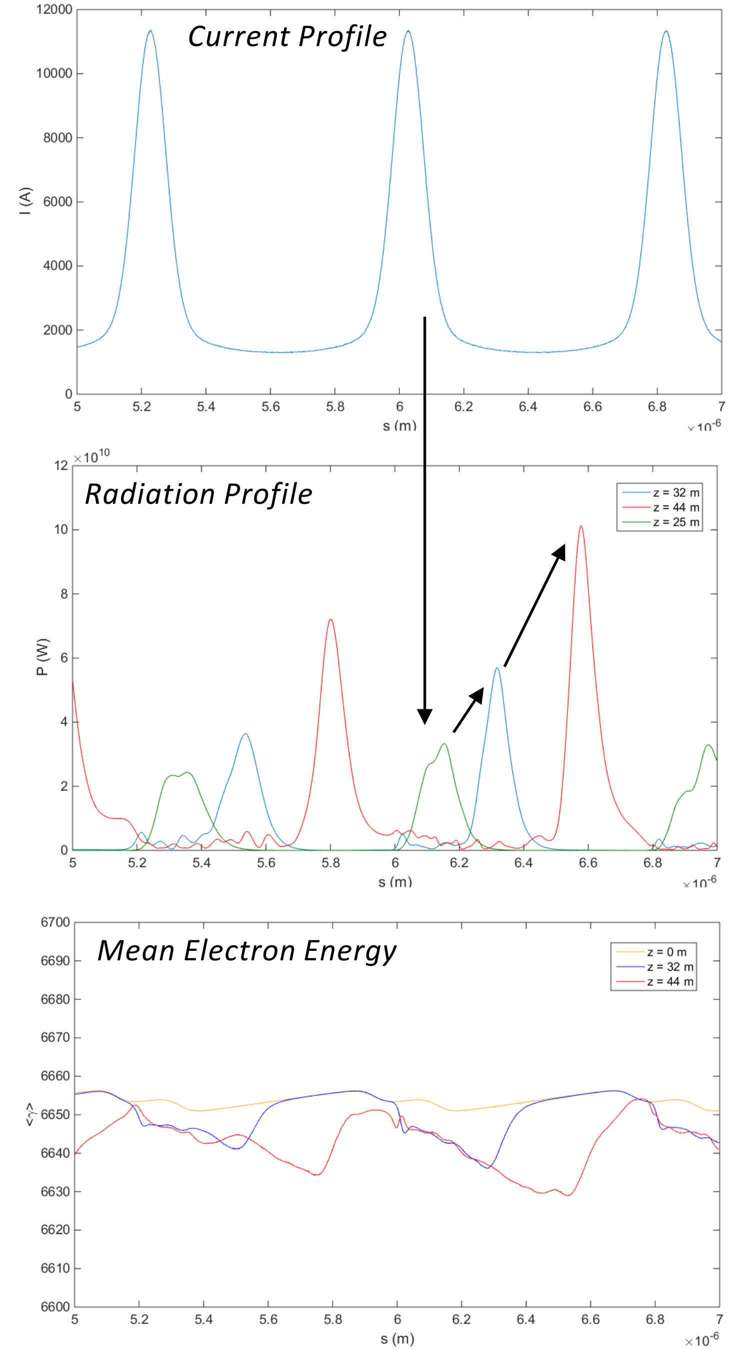
ESASE

- Model structure can be much more pronounced if an energy modulation is converted into a current distribution before the undulator.

- Requirement for the laser are reduced (example is for 400 MW, 100 μJ for 100 fs pulse length)

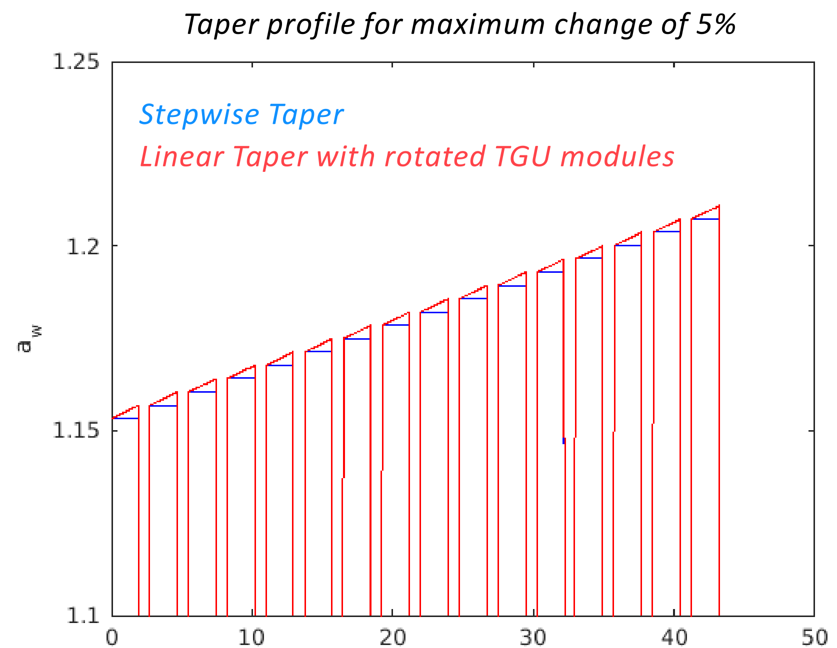
Typical characteristics:

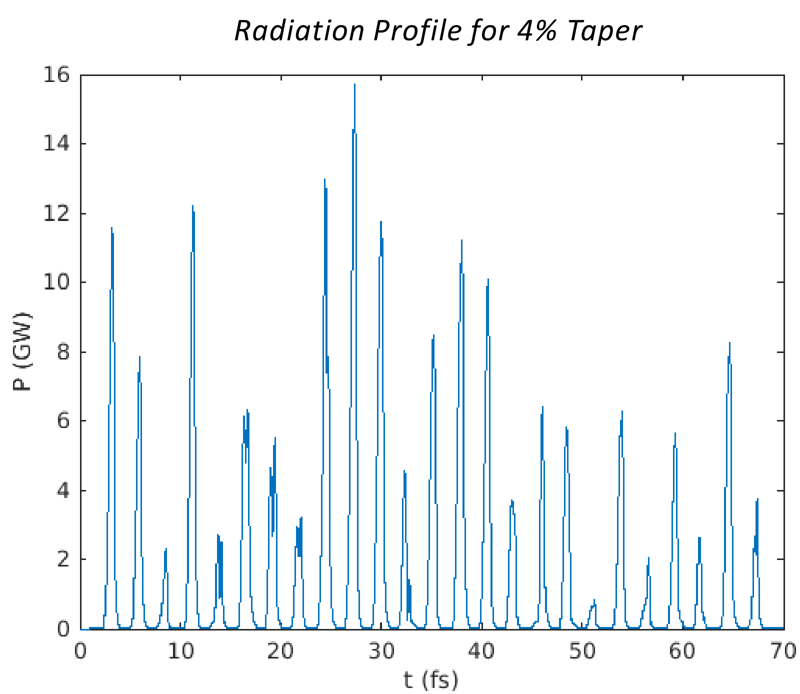
- *Modal structure much more clearer*
- *Superradiance growth after saturation over the "in between the current spikes" part of the bunch*
- *Short pulses (~300 as FWHM) after superradiant narrowing*

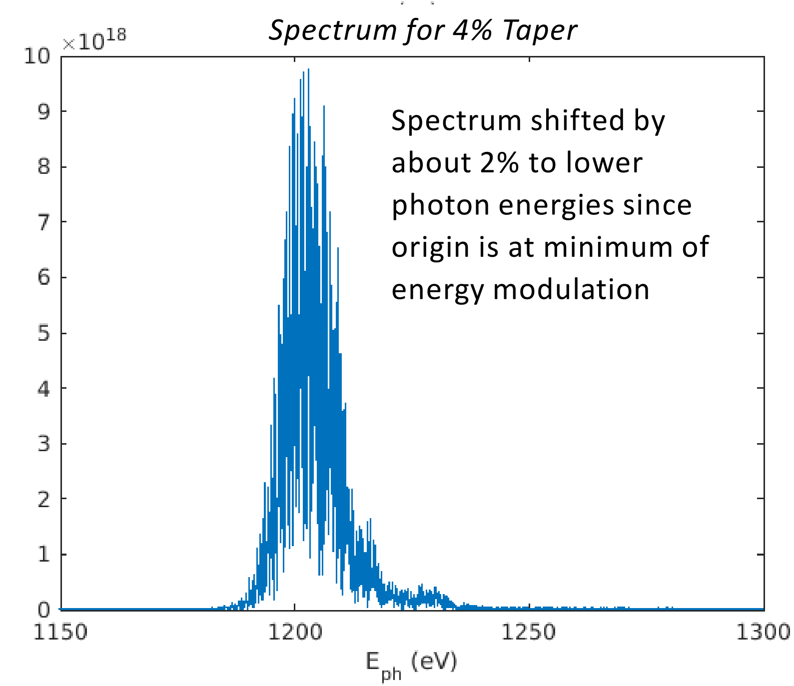


Slicing

- Instead of localizing radiation at a current spike, pulse is formed along rising slope in energy modulation
- Towards longer wavelength with stronger slippage an inter-undulator taper is needed (by means of TGU configuration), at 1 nm here a stepwise taper is sufficient.
- As ESASE drive laser period length defines spacing of radiation pulses.

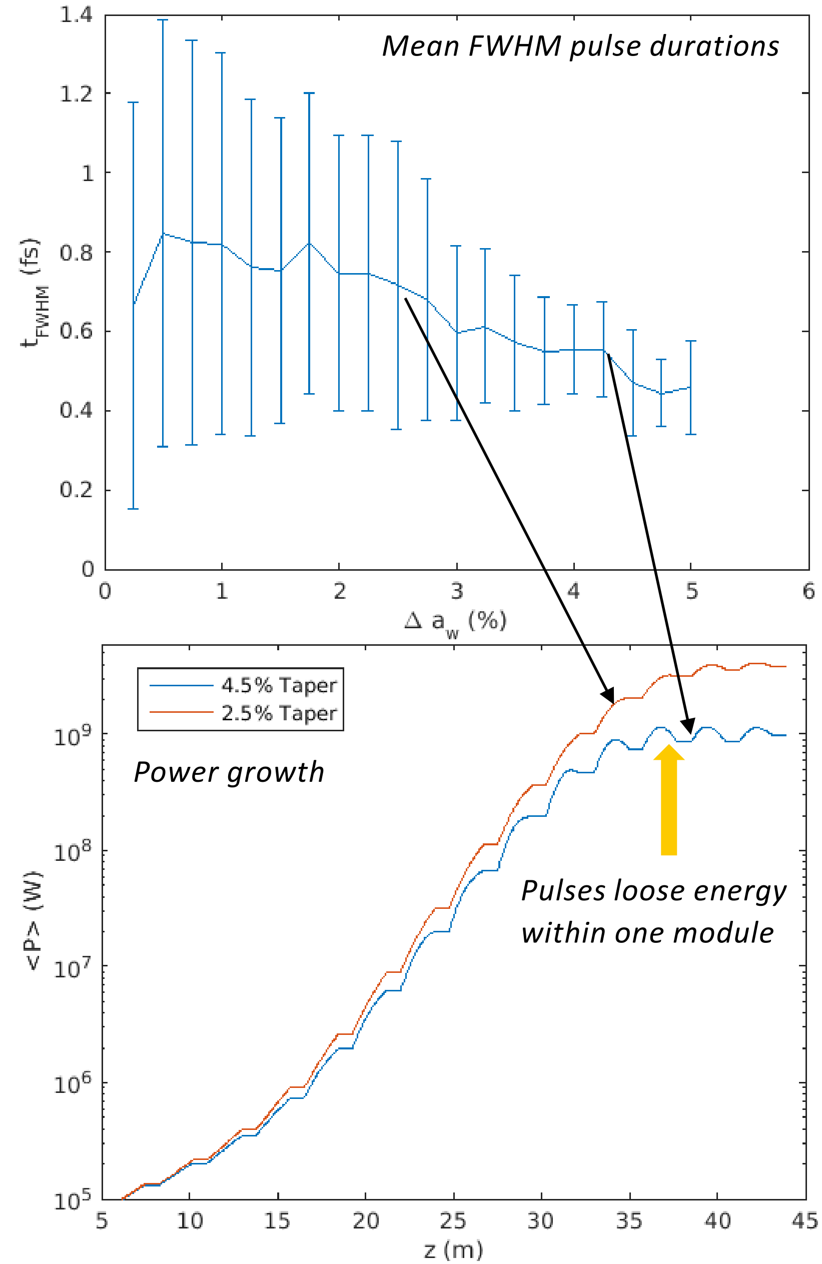




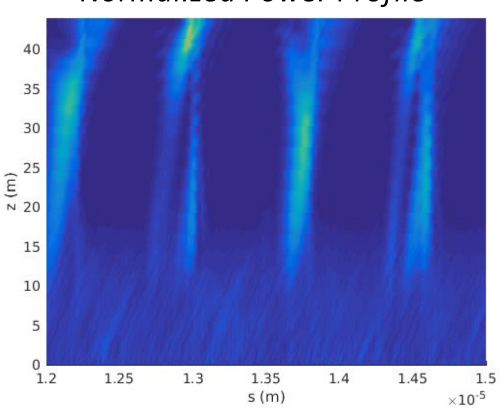


Slicing – Pulse Length Control

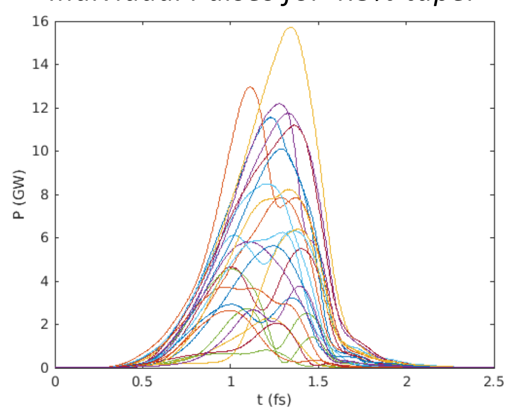
- Slicing offers a control on pulse duration by over-tapering with the cost of reduced output power
- Over-tapering makes the spike slip into absorption phase and gets "eaten" up at its head
- Ideal slippage length for "nearly" single spike" is a quarter seed wavelength for saturation.
- This can be further controlled with artificial delays (CHIC)
  - to enhance slippage at higher photon energies
  - To jump to next modulation at lower photon energies



Normalized Power Profile



Individual Pulses for 4.5% taper



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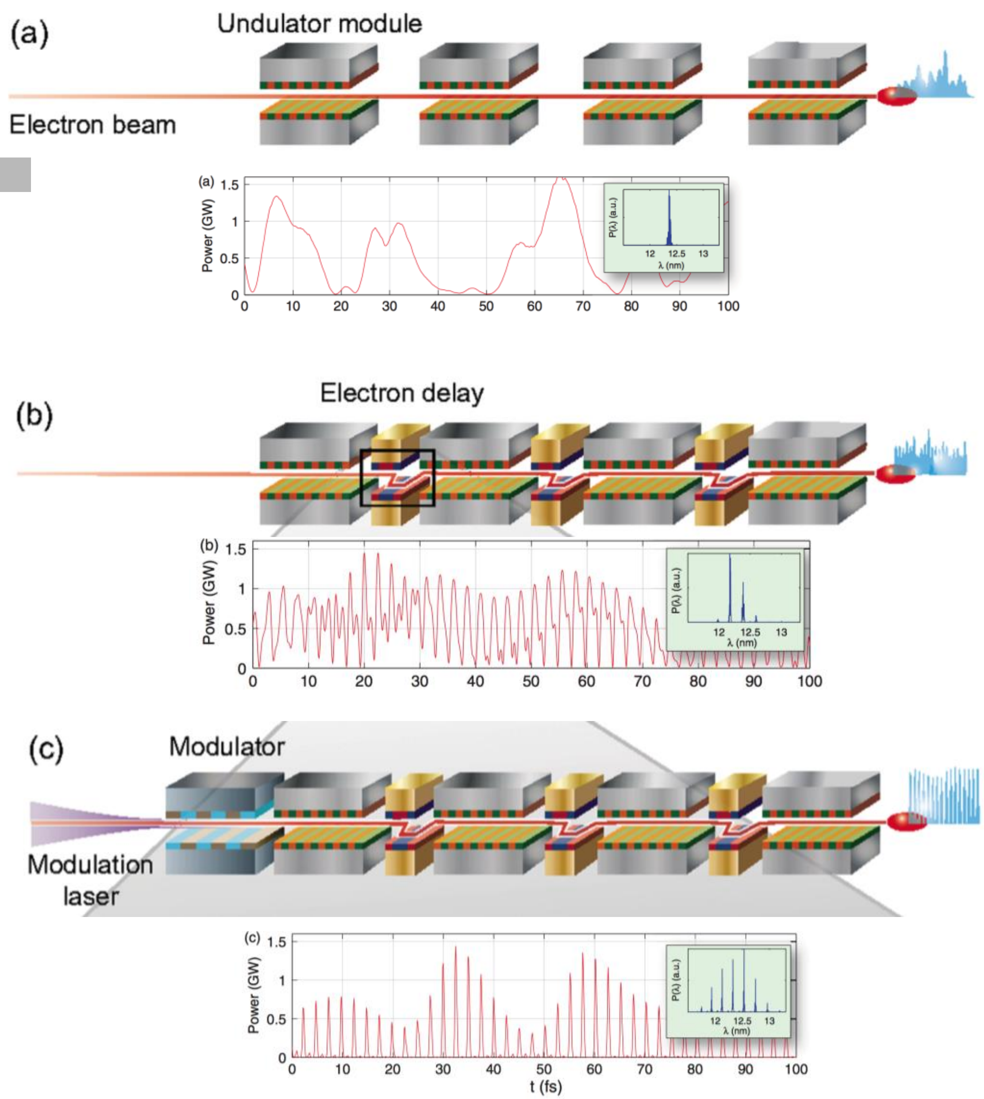
ESASE vs Slicing

ESASE	Slicing
Works better at higher photon energies	Works better at lower photon energies
Needs less energy modulation but requires chicane (CSR + LSC effects)	Needs only energy modulation but larger than ESASE
Gain length shorter than SASE	Gain length as for SASE or even longer for shorter pulses)
No control on single spike pulse length	Control on single spike pulse length
Might work better for Mode-locked lasing	Might work better for pulse length control by using CHIC
Supports isolated pulses with e-beam slicing (laser heater notch, emittance spoiler foil)	Supports isolated pulses with e-beam slicing (laser heater notch, emittance spoiler foil)

Mode-coupled and phase-locked pulses



SASE

The temporal output power is noisy, comprising phase-uncorrelated pulses (modes) with average separation $<2\pi l_c$,$l_c = \lambda/4\pi\rho$ the cooperation length)

Mode-coupled pulses

Increase of the cooperation length via chicanes, to couple between different SASE modes

Phase-locked pulses

By introducing an interaction modulation, the modes may become phase locked.

Temporal train of equally spaced, short, high-power pulses phase correlated over long distance

[N.R. Thompson, B. W. J. McNeil, PRL 100, 203901 (2008)]

Summary HERO modes

1. Attosecond pulse trains

2. Isolated attoseconds pulses with e-beam masking

3. Phase-locked pulse trains by either Mode-locked or coherent harmonic generation operation

4. Upgrade to EEHG configuration is straightforward.

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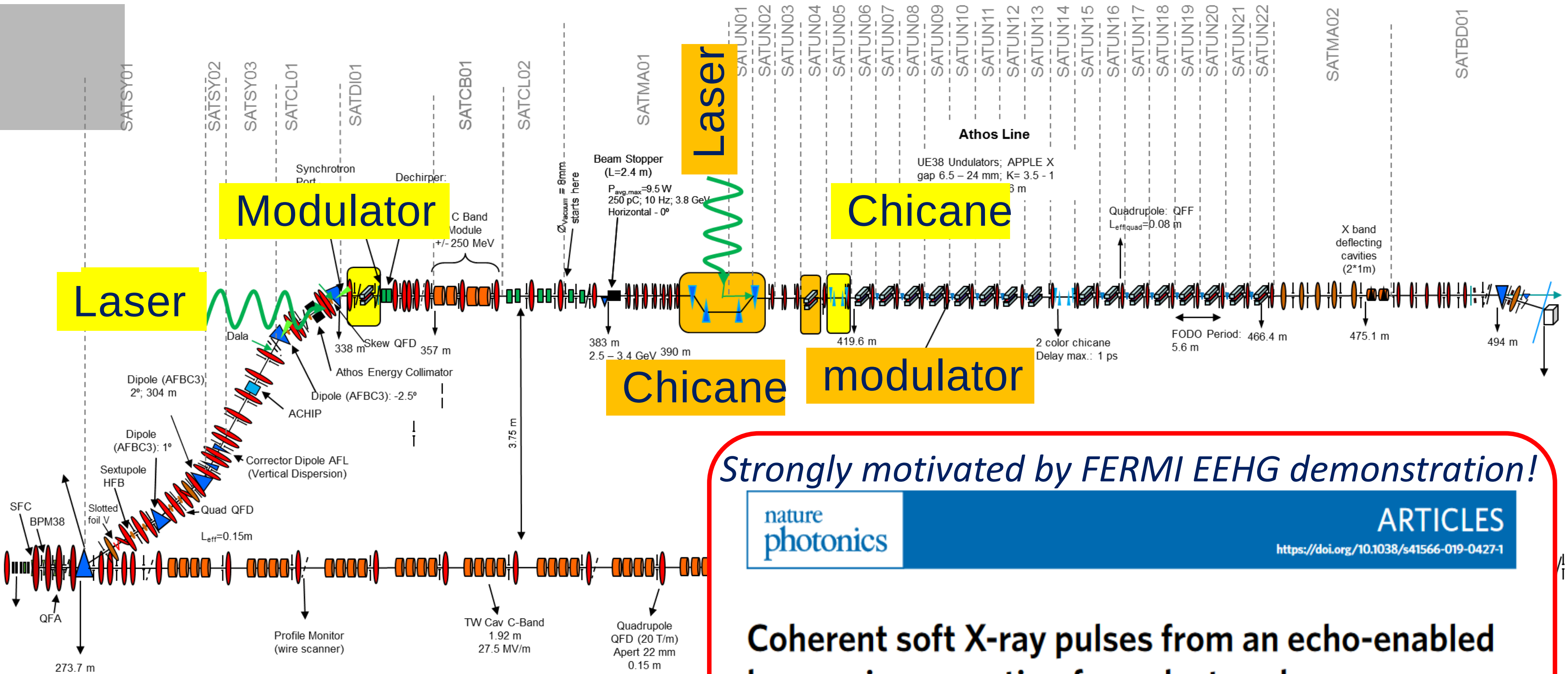
HERO + EEHG



Strongly motivated by FERMI EEHG demonstration!

nature photonics — ARTICLES

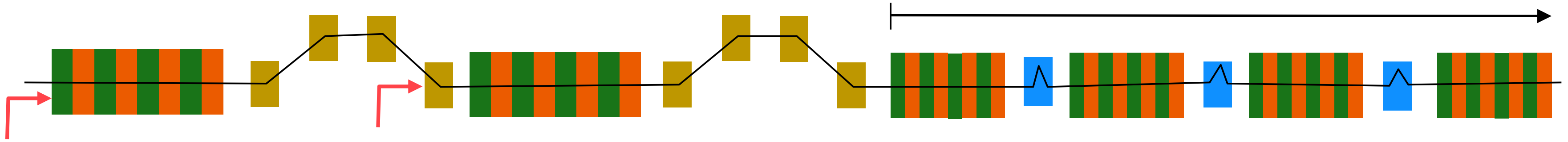
https://doi.org/10.1038/s41566-019-0427-1

Coherent soft X-ray pulses from an echo-enabled harmonic generation free-electron laser

HERO financed, implementation planned for 2021

EEHG looking for funding, implementation not before 2022

Echo-Enabled Harmonic Generation at Athos



- After successful demonstration at FERMI, re-evaluation for ATHOS.

- Six Parameters:
  - Seed wavenumber $k = 2\pi/\lambda_s$
  - Harmonic number h
  - Energy Modulation $A_{1,2} = \Delta E/\sigma_E$
  - Dispersion Strength $B_{1,2} = k\, R_{56}\, \sigma_E/E$

Scaling: $A_1 \approx 3$ $\quad A_2 \cdot B_2 \approx 1$ $\quad B_1 \approx hB_2$

Reaching high harmonics: $A_2 \cdot B_1 \approx h$

A_2 limited by heating up the energy spread, thus increasing the saturation length

B_1 limited by the practical length of the first dispersive section

EEHG at Athos (Case 1 – 1 nm)

FEL sensitive to increasing energy spread:

$$\sigma_E^{FEL} = \sigma_E \sqrt{1 + A_1^2 + A_2^2}$$

Assuming ideal compression (no LH, 500 keV @ 3 kA)

- I = 3 kA → $A_2 < 1.7$
- I = 6 kA → $A_2 < 1.7$
- I = 2 kA → $A_2 < 0.9$ ($A_1 = 2$)!

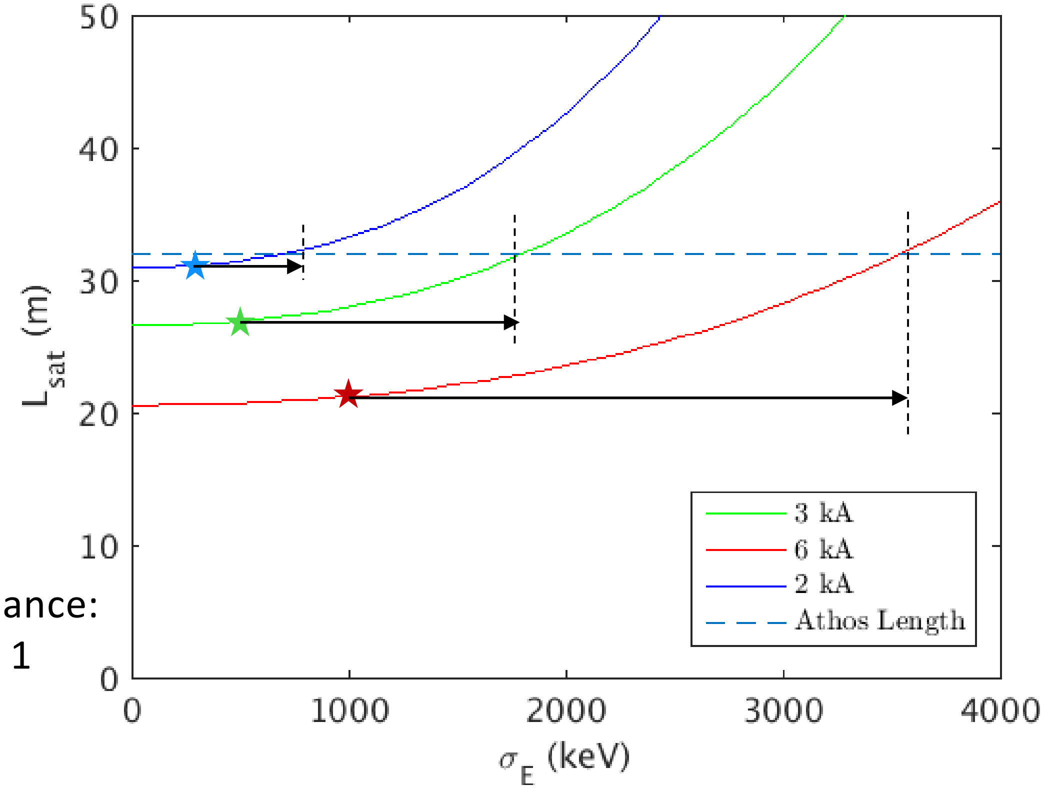
Consequences:

- Limitation in laser power
- Very strong chicanes (B_1=156)

➡ R_{56} = 40 mm

- Comparable to BC2 (17 m)
- Degradation by IBS + CSR
- Larger spread degrades performance:
  - 1 MeV @ 3 kA: $A_1 = 1$, $A_2 = 1$

Saturation length (Ming Xie Model)



EEHG at Athos (Case 1 – 4 nm)

- Situation more relaxed, no significant limitatio on energy modulation

A_2=3, B_1 = 30

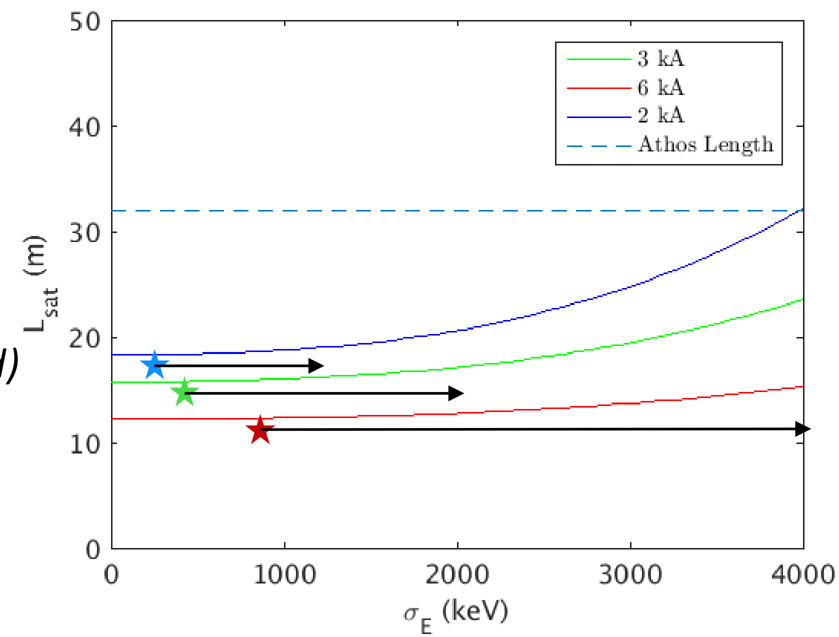
- For first chicane:

(initial energy spread)

R_{56} = 7.5 mm (500 keV @ 3kA)

R_{56} = 3.8 mm (1000 keV @ 3kA)

- BC1 estimate for relaxed operation:
  - Bending angle: 2 degree
  - Total length: 4 m
- For second chicane: R56 < 100 μm (two-color chicane)



<2 nm might be possible (harmonic EEHG) with same hardware

Full compressed 10 pC as-pulse enabled by large chicane

Upgrade from ESASE/Slicing configuration:

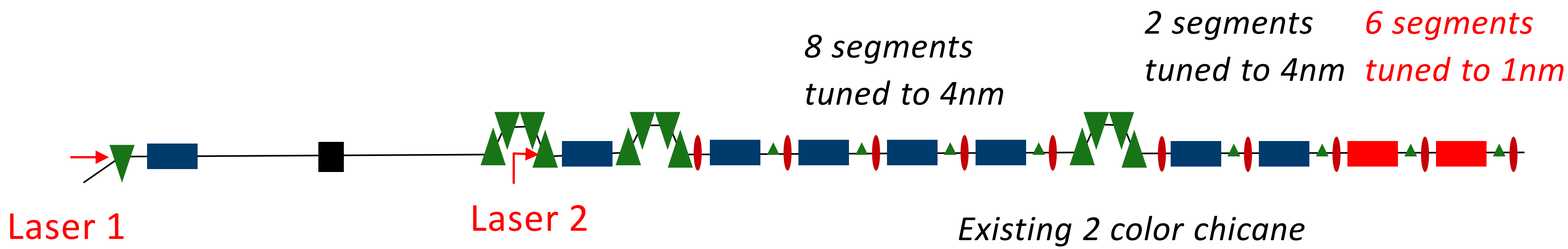
- ***About 5 m for first chicane***
- ***About 2 m for second modulator***
- ***Second seed laser (possible split of slicing laser)***

EEHG summary

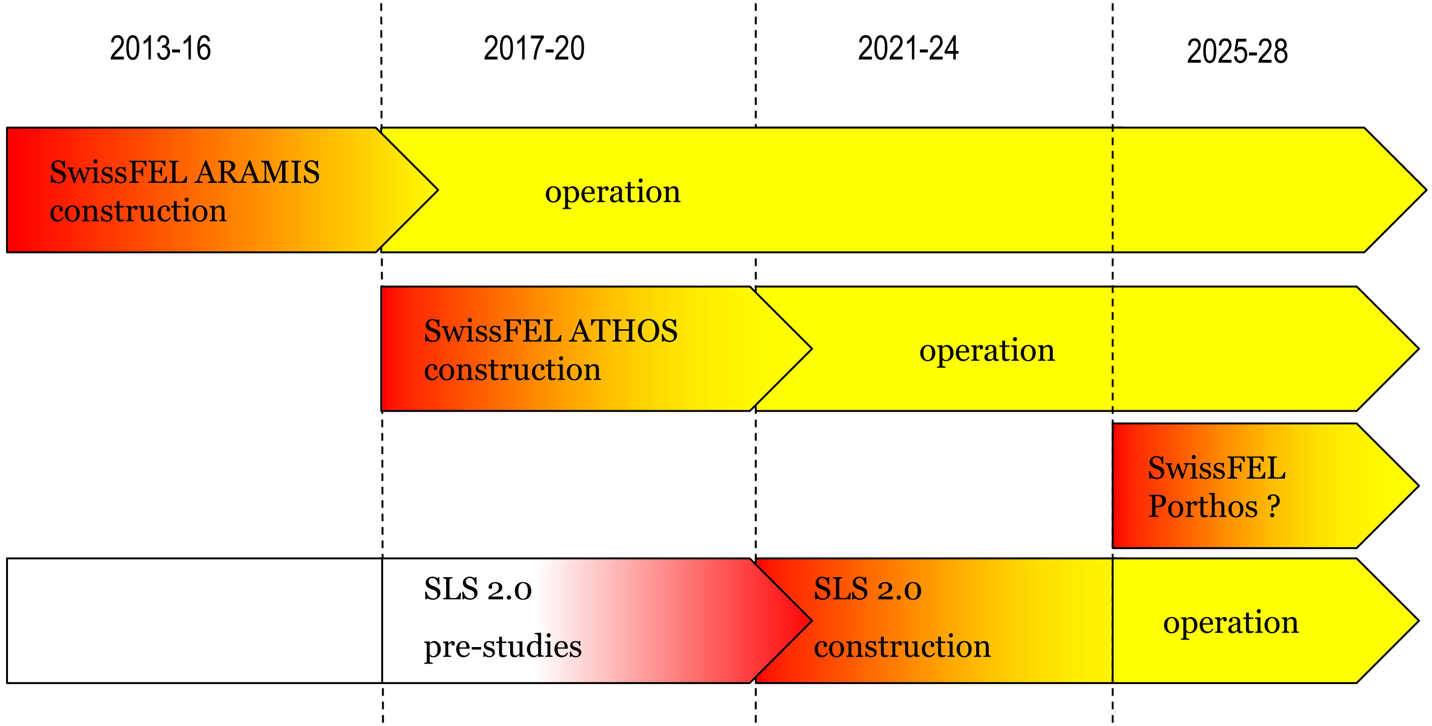
“Standard“ EEHG promising for $\lambda\approx$2-4nm

For $\lambda\approx$1-2nm required A_2 energy spread too large for acceptable gain length

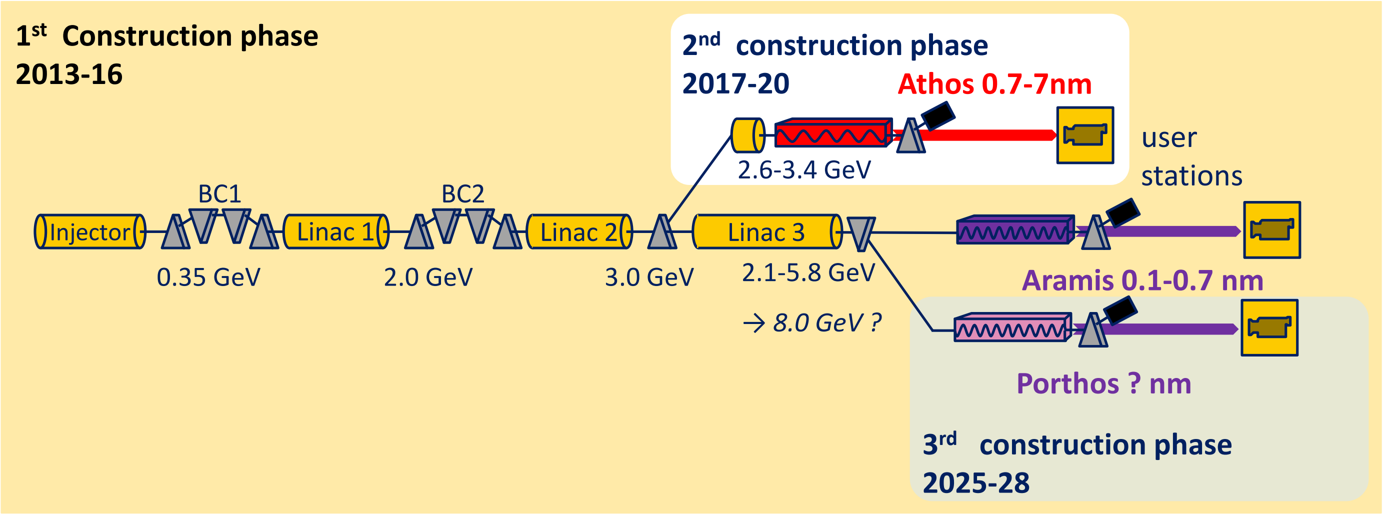
$\Rightarrow$ EEHG + HGHG stage with fresh bunch under study
for 1 nm lasing with external seeding



Photon facility roadmap

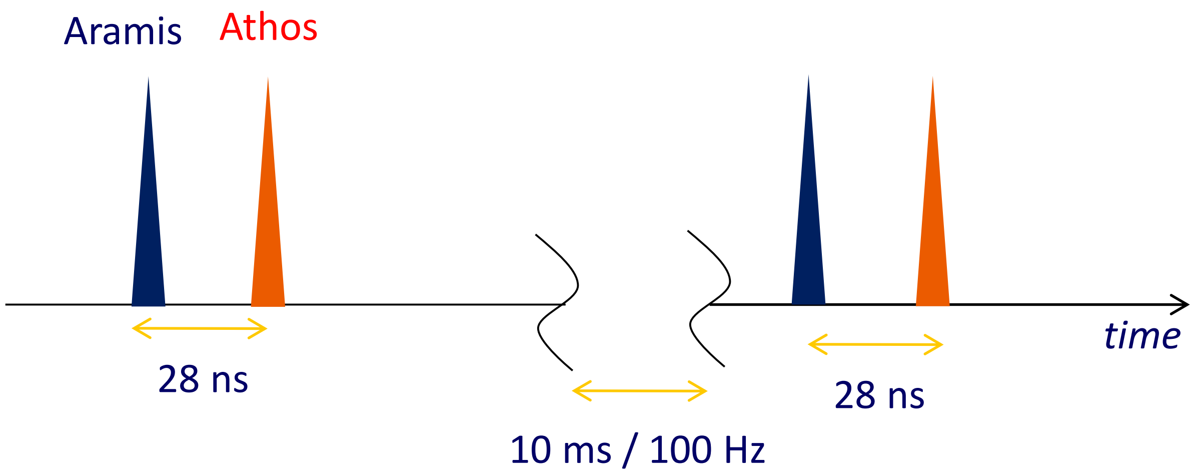


SwissFEL



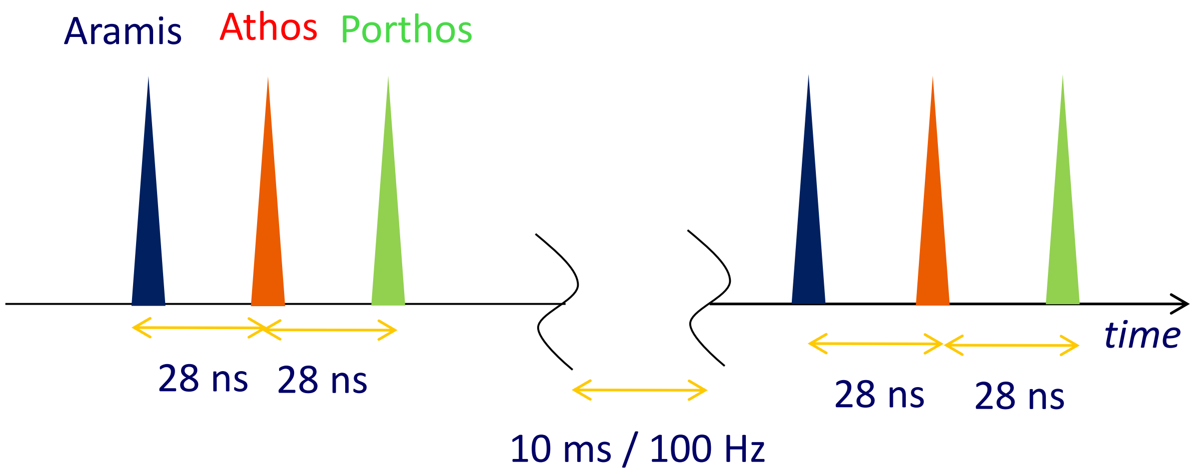
1st Construction phase
2013-16
2nd construction phase
2017-20
Athos 0.7-7nm
user
stations
2.6-3.4 GeV
BC1
BC2
Injector
Linac 1
Linac 2
Linac 3
0.35 GeV
2.0 GeV
3.0 GeV
2.1-5.8 GeV
→ 8.0 GeV ?
Aramis 0.1-0.7 nm
Porthos ? nm
3rd construction phase
2025-28

time structure with Athos



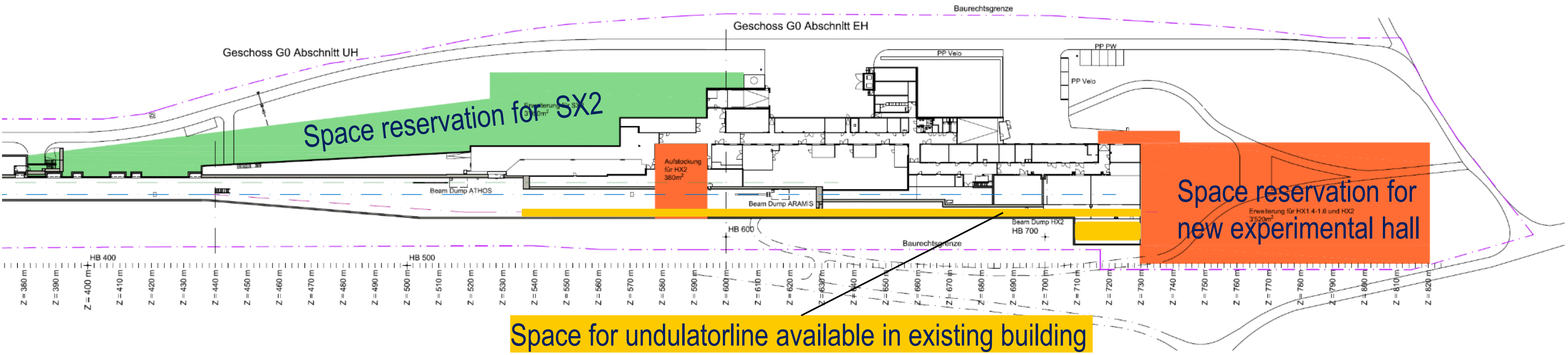
Fast extraction at 3 GeV allows to serve 2 undulator lines simultaneously at full 100Hz repetition rate

time structure with Athos and Porthos



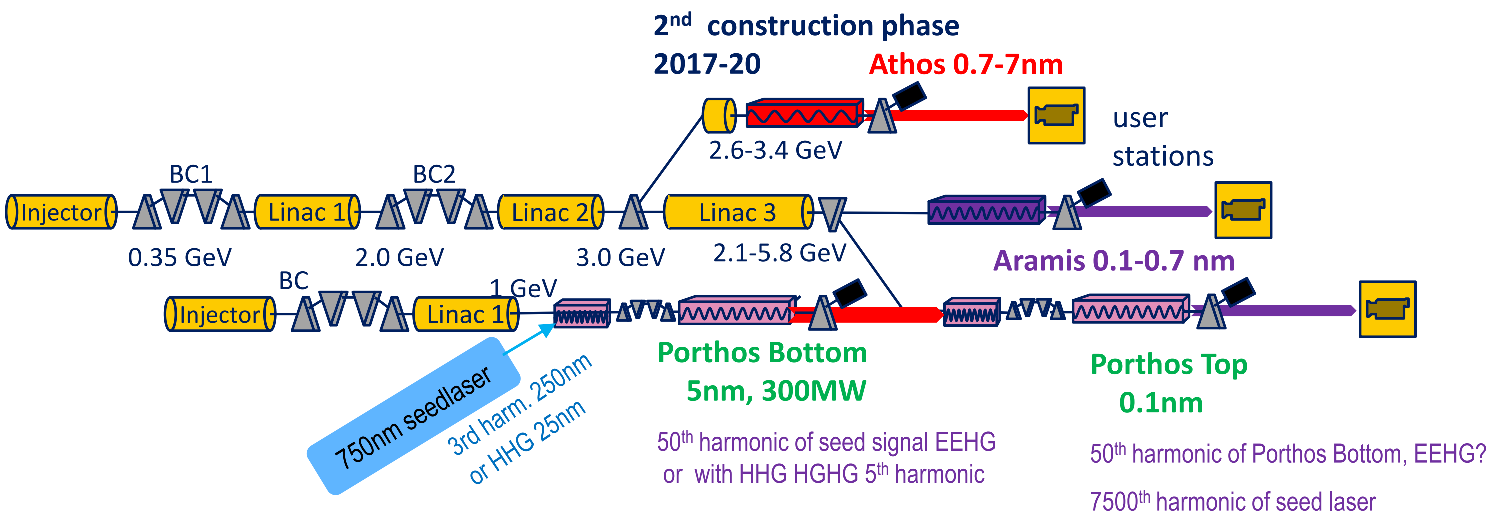
Fast extractions at 3 GeV and 5.8 GeV allow to serve 3 undulator lines simultaneously at full 100Hz repetition rate

Zoom-in SwissFEL Extensions



Porthos option C: “FEL² seeding”

similar photon energy as Aramis but with external seeding from second low energy FEL



Promises full coherent control at shortest wavelength

Key R&D on FEL physics, seed laser and timing tolerances required

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Summary

ATHOS, the 2nd FEL line of SwissFEL dedicated to soft X-rays,
is starting beam commissioning now.

ATHOS capabilities will be augmented in 2021 with the HERO set-up for beam manipulation by a dedicated TiSa laser, a modulator-undulator and a R_{56} chicane.

EEHG is a logical extension of the HERO set-up, pushing the wavelength of EEHG to 1nm.
EEHG is presently under consideration for ≥2022.

One option for the long term, ≥2025, evolution of SwissFEL is a 3rd FEL line PORTHOS with an external seeding scheme.