Summary WG A

Linca Based Light Sources

Working Group-A (Linac Based Light Sources) session overview

- Statistics
  - Abstracts 63
  - Invited talks 16
  - Contributed talks 13
  - Posters 29

- Parallel session themes

–	MO3	Status of facilities	9 talks
–	TU2	Coherence	4 talks
–	WE2	e beam & FEL physics	4 talks
–	WE3	High duty cycle & Injectors	6 talks
–	TH2	Short pulses	4 talks
–	TH4	Novel concept	4 talks

  - User's talk (invited) 12+3 min.
  - Contribution talks 12+3 min.
  - Discussion 30 min.

- In the first session, we had status reports from 9 FEL facilities.
- For the remaining sessions, we decided on the topics to discuss, and selected talks with content appropriate to those topics.
- ....however, there were some mismatches occurred when the talks actually proceeded.

- Time for discussion was set aside at the end of each session for full discussion.
- In many sessions, talk from experimental users were included as a source of discussion.

TH4 Novel Concepts

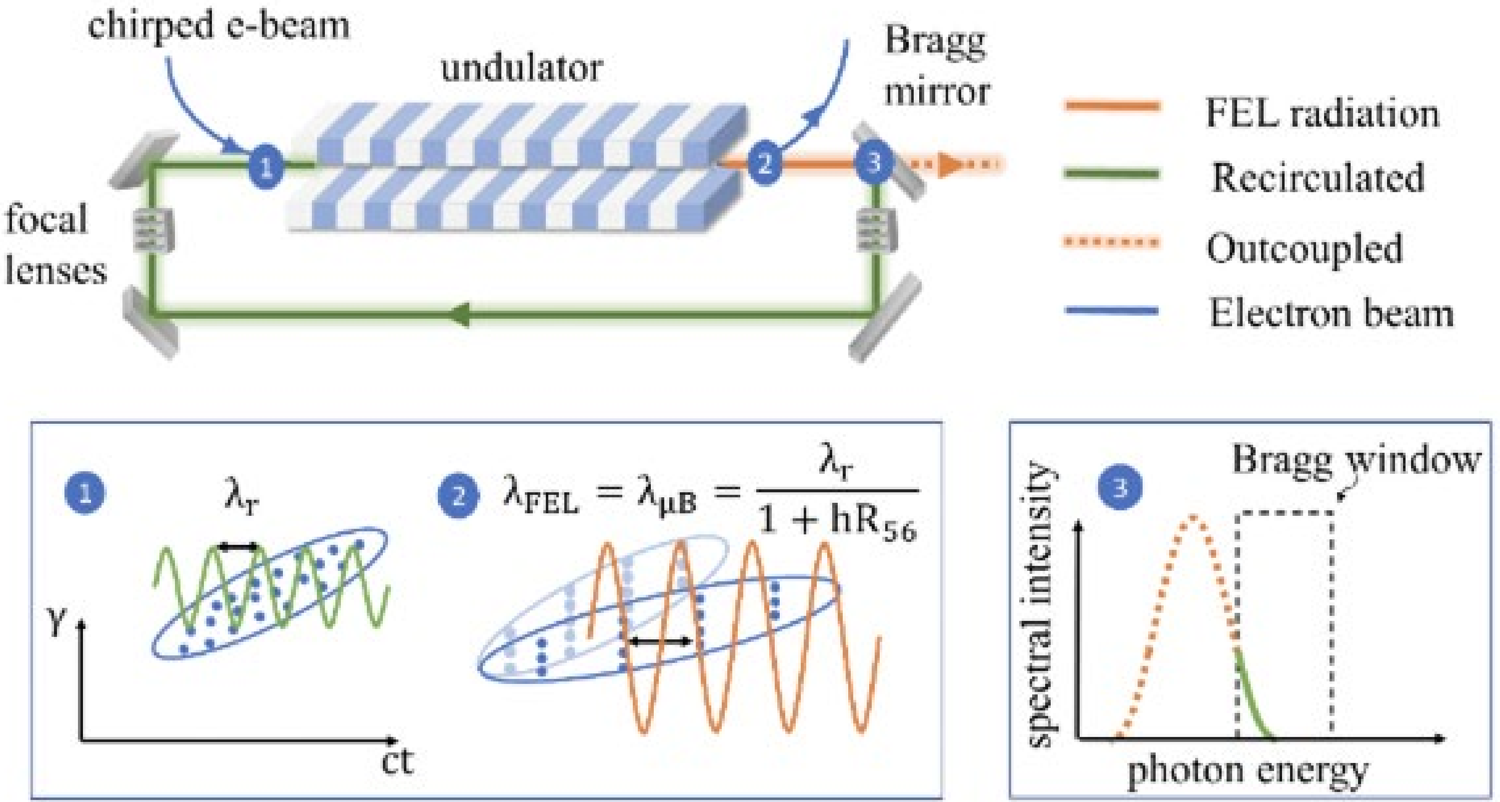
Conclusions

We presented an advanced conceptual design of a **compact ICS source:**

- S-band **photoinjector**
- High-gradient multi-bunch **X-band acceleration**
- **Fabry-Pérot** cavity operating **in burst mode**

Realistic start-to-end simulations were performed, showing that the HPCI-ICS source has the potential to produce 2 MeV gamma rays with a **total flux of 2.2 x 10^{13} ph/s in less than 15 meters** in length. It's one of the most compact, high energy and high flux sources in the landscape of existing and planned ICS sources.

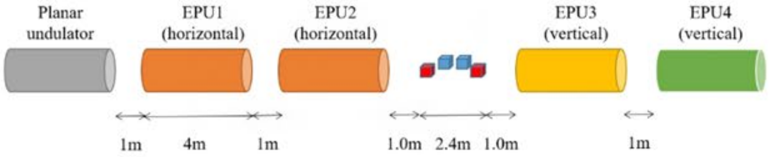
MeV energy range gamma rays can have applications in various fields: material science, medicine, nuclear physics research, homeland security by nuclear resonance fluorescence inspection, and non-destructive testing of industrial materials.

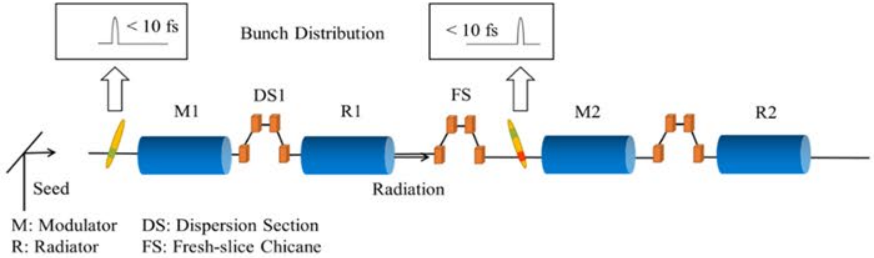


- **A simple, beam-based, active Q-switching method**

Summary

- Pulse-by-pulse polarization switch over 85% polarization degree at different wavelengths under SASE mode in FEL-II in simulation.
- Several-femtosecond-long FEL pulses under EEHG as well as cascaded HGHG mode in SXFEL in simulation.
- Both linearly and circularly polarized femtosecond FEL pulses with different wavelengths at the same time on axis.
- A series of jitter and parameter analyses in both designs.



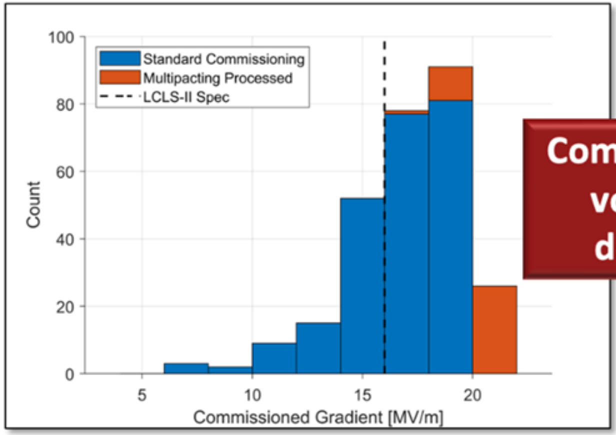


MO3 Status of Facilities

LCLS-II Commissioning Status

Linac Commissioning

- ✓ Established the **first-time beam through the main SC linac** in October 2022
- ✓ **3.5 GeV beam** demonstrated in November 2022
- ✓ **Record injector performance** has been demonstrated
- ✓ Demonstration of **repetition rate of 93 kHz** in June 2023

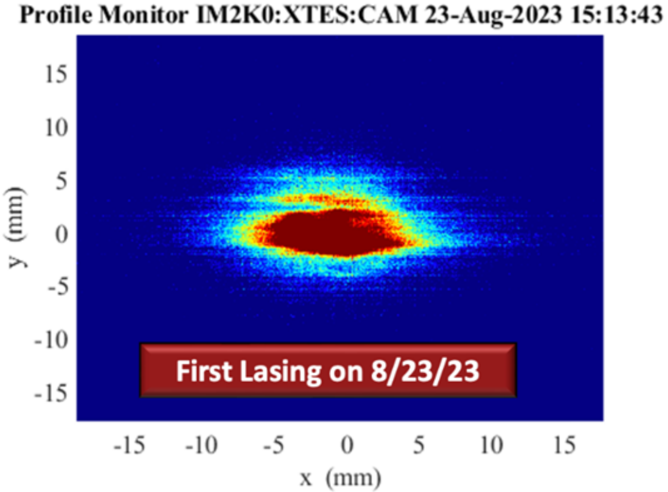


Commissioned cavity voltage exceeds design by >20%

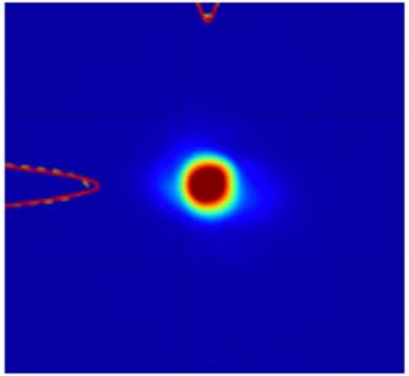
Photon Commissioning

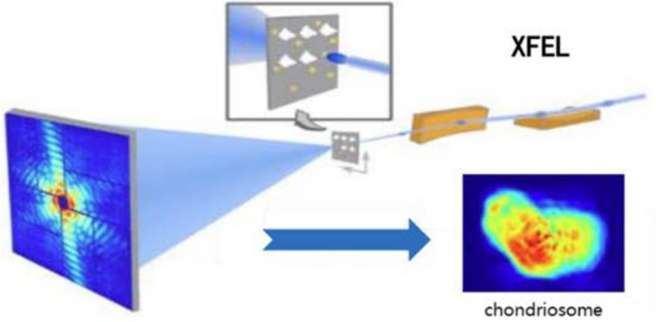
- ✓ Beam transport to undulator halls in August 2023
- ✓ First photons in August 2023

3. Verification of photon energy – **estimate to complete in September**



SXFEL：Shanghai Soft X-ray FEL Facility





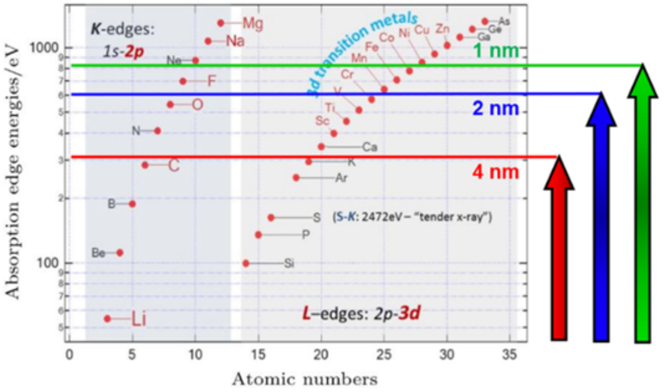
- The main parameters of linac and FEL have all reached or exceeded the design values in 2022, open for users this year.
- Can operate with SASE or seeding modes: lasing of SASE with the shortest wavelength of 2 nm, lasing of EEHG at 5.6 nm (47th harmonic), and got coherent signal at 4.3 nm (61st harmonic), lasing of EEHG cascade at 8.8 nm (30^{th} harmonic) and got coherent signal at 5.3 nm (50^{th} harmonic).
- Beam lines and end-stations are under commissioning.
- The first round of user experiments has been launched (supported ~10 user teams).
- Advanced experiments for flexible control of the FEL properties are in preparation.

Summary slide – MO3A8

Elettra Sincrotrone Trieste

SCIENTIFIC NEEDS

- Resonant processes of few fs-lifetime
- Nonlinear optics (large wave-vectors)
- Ultra-fast chemistry & Chirality
- Water window
- Coherent control



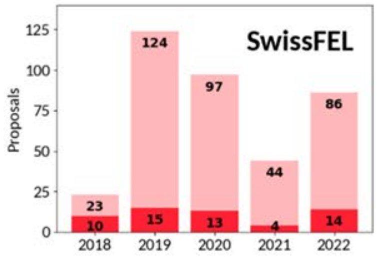
UPGRADE PLAN

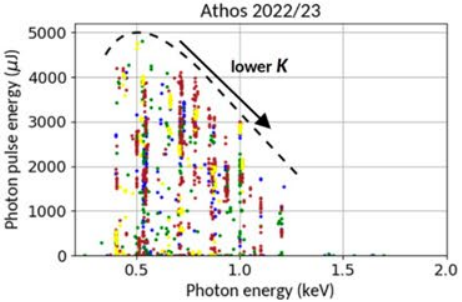
- **Linac energy** upgrade with high gradient, low impedance S-band structures → *ONGOING*
- **FEL-1** upgrade to **EEHG** → *ONGOING*
- **FEL-2** upgrade to **EEHG-FB** (long term)
- **Seed lasers** upgrade to shorter duration, larger spectral tuning

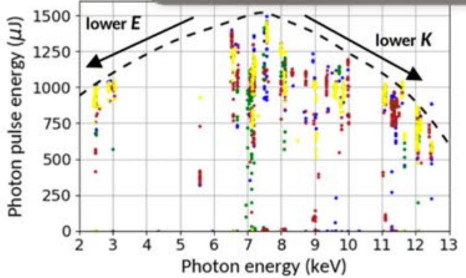
Shorter Δt (<10 fs)
Shorter λ (N,O K-edge)
Longitudinal coherence

PAUL SCHERRER INSTITUT

SwissFEL







Aramis advanced modes – overview

Short pulses ✔
(beam tilt)

Large bandwidth mode ✔
(large energy chirp from linac wakefields)

"Attosecond" pulses ✔
(three-stage compression)

Large bandwidth mode with spatial chirp ✔
(additional spatial chirp from dispersion in undulator)

✔ ready for experiments!

Athos advanced modes – overview

not yet attempted
in commissioning
✔ ready for experiments!

(Optical klystron) ✔

Short pulses ✔
(beam tilt)

Variable polarization ✔

Large bandwidth
(energy chirp)

Two-color with fresh slices ✔

Ultralarge bandwidth
(TGU)

Short-pulse high-power ✔
(superradiance)

High-brightness SASE

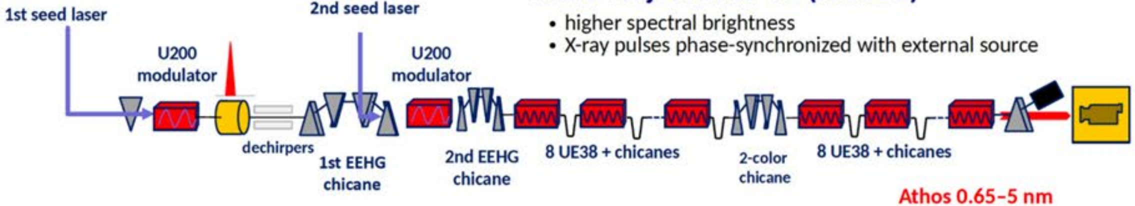
"Attosecond" pulses ✔
(three-stage compression)

Laser seeded modes:

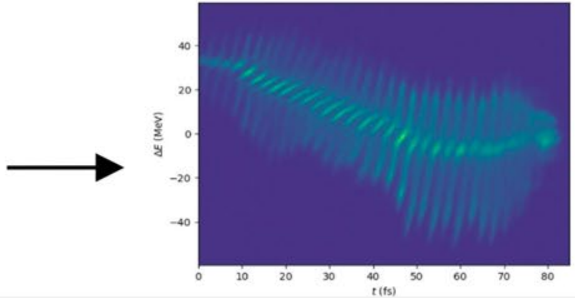
Enhanced SASE ✔	**Mode-locked lasing**	**Echo-enabled harmonic generation (EEHG)**

EEHG Project 2021–23 (Phase 2)

- higher spectral brightness
- X-ray pulses phase-synchronized with external source

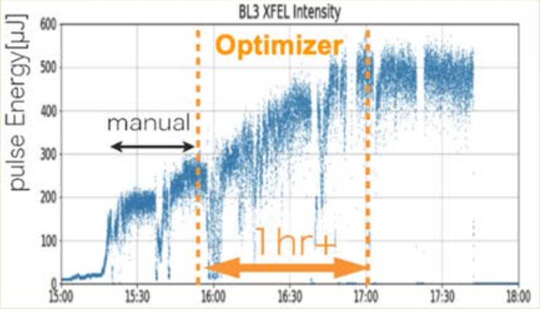


Athos 0.65–5 nm

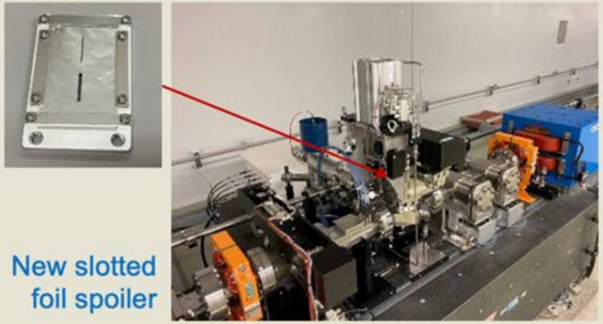


MO3A7 Status and upgrading of SACLA

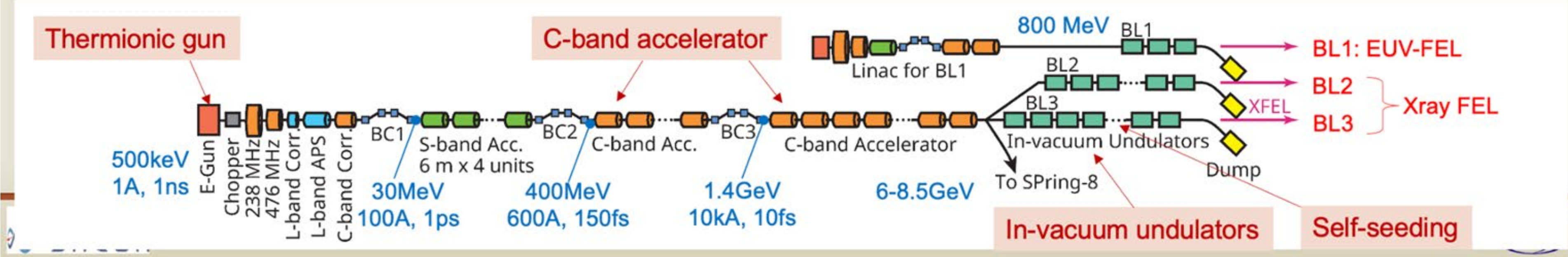
- Operation status
  - 2 XFEL beamlines (4-22keV) and 1 EUV-FEL beamline (40-150 eV)
  - Top-up injection of 8 GeV beam to SPring-8 storage ring
  - Operate 6,000 hours/year with high availability
  - Self-seeding, two color, SDO, sub-10 nm focus, high power fs lasers, …
- On-going updates
  - Pulse-to-pulse beam control using reflective memory network
  - Short pulse length manipulation using slotted foil spoiler
  - Machine learning (GPR) based beam tuning optimizer
- Future upgrade plan
  - High repetition rate (~600 Hz) operation using normal conducting RF
  - Maintain electricity consumption, for "Green facility"



SASE pulse energy increase using machine learning GPR optimizer



New slotted foil spoiler



TH2 Short Pulses

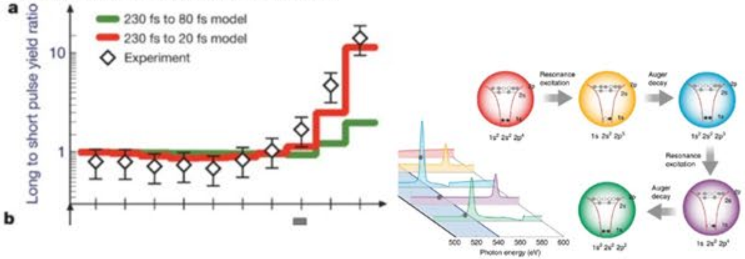
Short Free-electron Laser Pulses: The User Perspective (Bostedt, Th2A)

- Notes:
  - **Core-vacancy lifetime natural clock** for XFEL experiments
  - **Demonstrated relevance (damage) of pulse length** for established XFEL applications (ultrafast diffraction, imaging, spectroscopy)
  - New **opportunities for truly non-linear spectroscopy** in attosecond domain

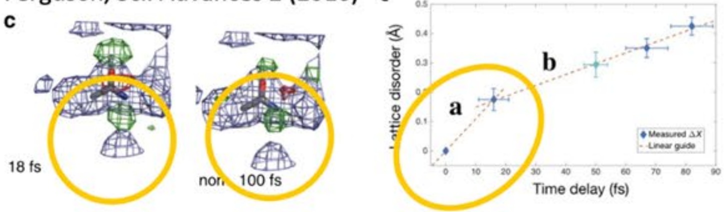
- Conclusions:
  - For most applications **figure of merrit should be «photons per femtosecond»** and pulse length should be few to few tens of femtoseconds.
  - **Attosecond generation and application provide unique opportunities** at the time-resolution frontier and for truly non-linear X-ray spectroscopy.

- Famous last words:
  - **Two X-ray pulses are always better than one** – for pump/probe applications.

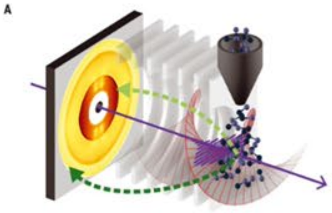
Impact: fundamental processes, Young et al, Nature 466 (2010), Ho, Nature Comm 11 (2020).

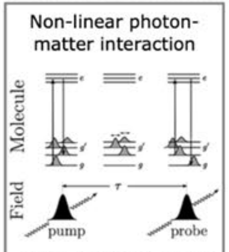


Impact: damage discussions, Nass et al., Nature Comm. 11, (2020), Ferguson, Sci. Advances 2 (2016)



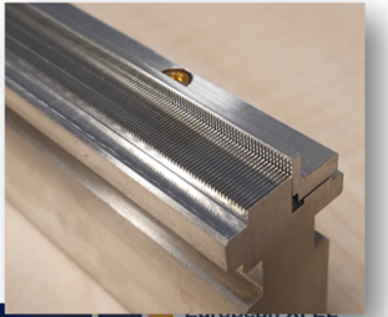
Opportunities at non-linear X-ary and time-resolution frontier, Li et al., Science. 375, (2022)

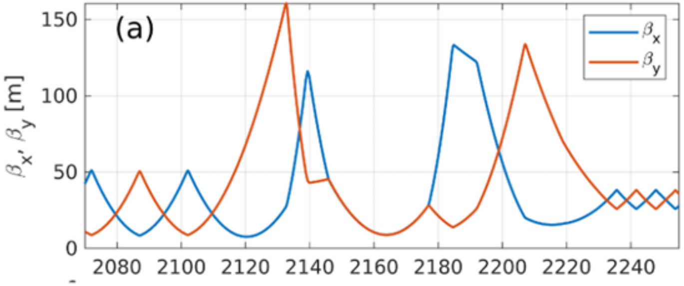


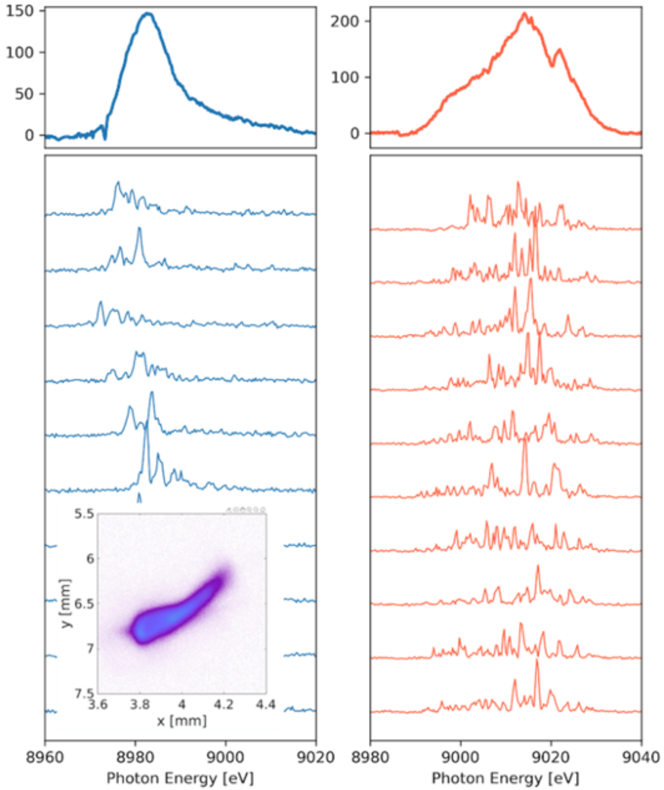


Biggs et al., PNAS 110, 15597 (2013)

- We have developed a corrugated structure system for fresh-slice applications at the European XFEL based on novel L-shape design.
- The L-shape design features variable streaking direction and the possibility to cancel quadrupole component from flat geometry.
- The L-shaped system has been installed before SASE1/3 branch and has been commissioned.
- Detailed study of the structure (calibration, quadrupole effect, high rep. rate) and FEL lasing control using the system is ongoing. Beam loss issue will be further investigated with Marvin robot







Summary

- Pulse-by-pulse polarization switch over 85% polarization degree under SASE mode.
- Femtosecond FEL pulse under EEHG/cascaded HGHG mode.
- Both linearly and circularly polarized femtosecond FEL.
- A series of jitter analysis.

Conclusion

1. Demonstrated fresh-slice multi-stage amplification scheme in Athos with beam tilt

2. Efficient amplification with up to 4 stages

3. Pulses with mJ energies and few fs duration for 0.5 and 1 keV

4. Mode already used in Athos (data under analysis)

5. Outlook: MSA amplification with ESASE

TU2 Coherence

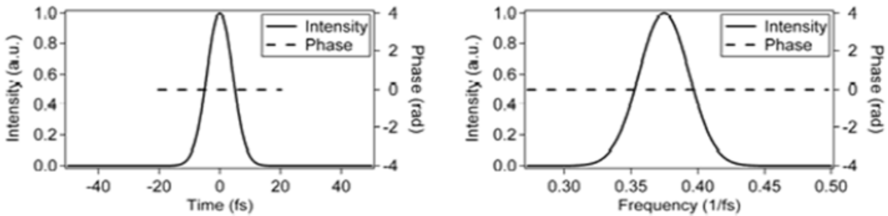
Are transform-limited pulses the Holy Grail for all user experiments?

Giovanni de Ninno (Elettra-Sincrotrone Trieste)

"Standard users" say:

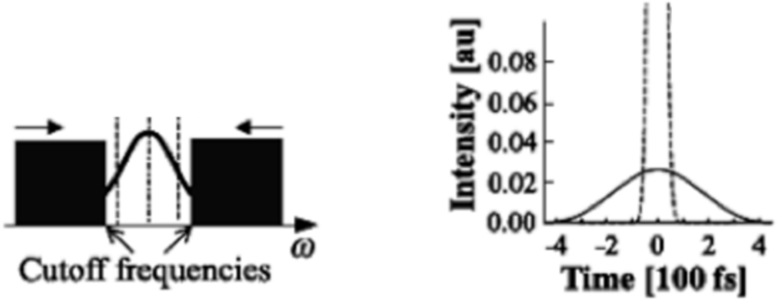
Give me transform-limited pulses!

Need of ultra-short **or** monochromatic pulses
Four-wave mixing



"Advanced" FEL users say:

Give me transform-limited pulses, with adjustable spectro-temporal shapes!



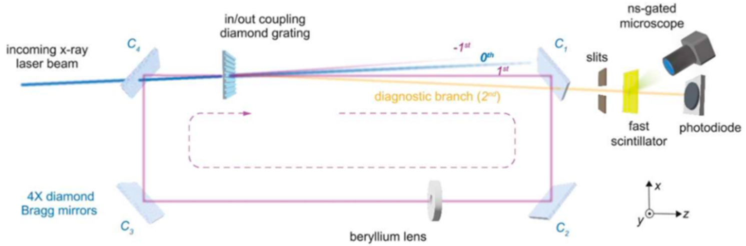
Coherent quantum control

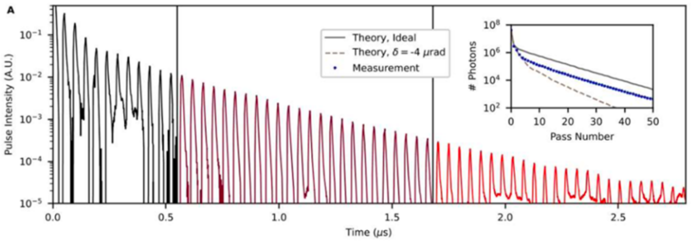
Picture from: Dudovich et al., PRL 2001

A Low-Loss 14 m Hard X-ray Bragg-reflecting Cavity, Experiments and Analysis

Rachel Margraf, TU2A4

- Built a 14 m X-ray cavity at 9.8 keV with 4 diamond mirrors.
- Observed ringdown with up to 60 passes, and 88% efficiency at high passes, and 88% efficiency at high pass numbers, and <1% loss per mirror, close to theoretical reflectivity.
- Tested mirrors, diagnostics, focusing and alignment techniques in preparation for a cavity-based XFEL.
- The Cavity-based XFEL (CBXFEL) project will build a 2-pass gain, 66 m demonstration cavity in the LCLS Hard X-ray undulator hall within the next year. The two-bunch mode of the normal-conducting linac will be used to provide two electron bunches spaced at 220 ns.





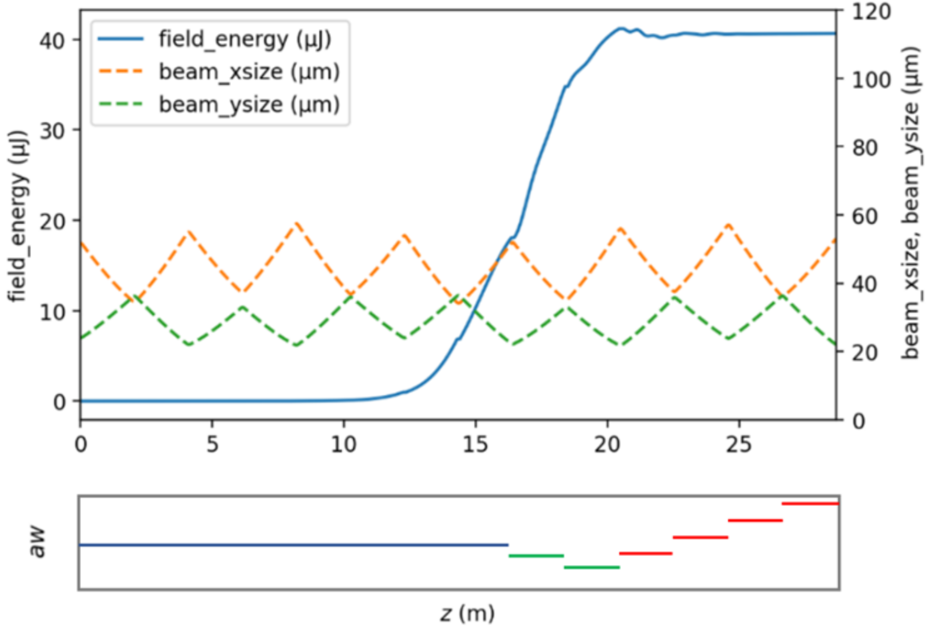
R. Margraf *et al.*, *Nat. Photonics*, (2023)

- Once LCLS-II HE is online, raising LCLS-II's energy from 4 GeV to 8 GeV we will have high energy electrons at high repetition rates, matching the round-trip time of the cavity, and can build a user-scale CBXFEL.

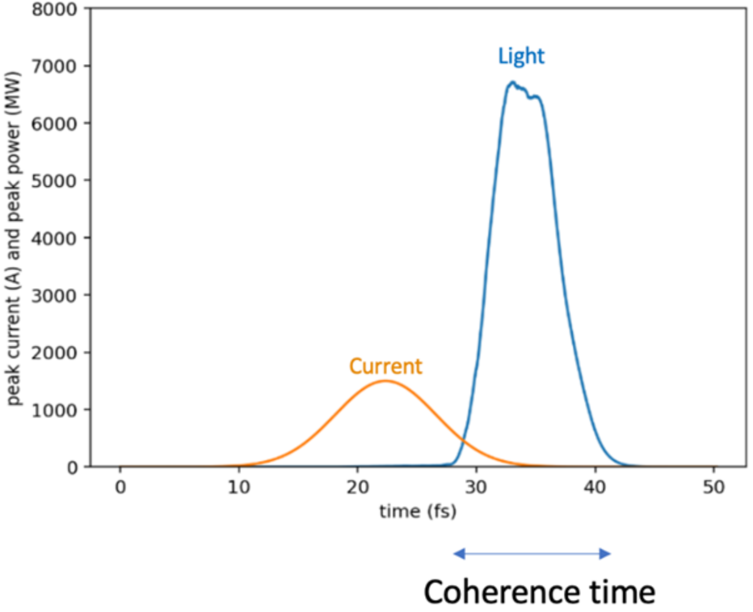
TU2A2 Summary Slide

Dinh Cong Nguyen (xLight)

STU-SASE pulse energy vs. position along undulators



Electron peak current & light power vs. time

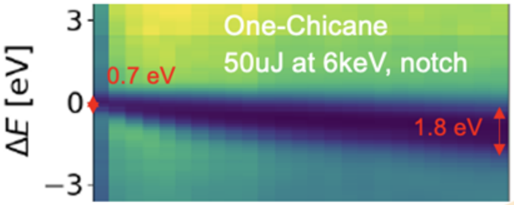


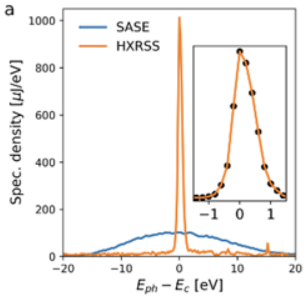
We show the slippage-dominated tapered undulator SASE (STU-SASE) can generate single-spike soft X-ray pulses without seeding. The pulse-to-pulse amplitude fluctuations in the exponential regime are consistent with 1 to 2 longitudinal modes. The STU-SASE spectra exhibits narrow linewidth due to its long coherence time.

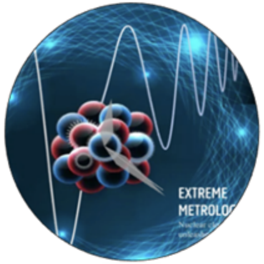
Opportunities and Challenges of the Hard X-ray Self-seeding System at the European XFEL

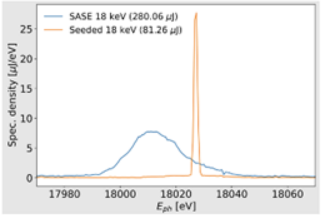
Requests from Users

- Higher photon energy
- Fast tuning
- High intensity
- Low background
- Narrow bandwidth
- Stability









6-7 keV → 9-10 keV → 12-14 keV → > 18 keV

- Heat load problem at lower photon energy
- Peak performance of 1 mJ/eV at 9-10 keV
- Narrow BW requests for higher photon energies
- Even higher photon energies

WE3 High Duty Cycle & Injectors

Romain Letrun (EuXFEL)

High pulse rate photon experiments - Current status and future directions

- Operation up to hundreds of kHz ideal for many classes of experiments, preferably CW
  - Sample delivery limitations/best use of sample
- MHz repetition rate has so far limited, but very interesting applications
  - Enables improvement of existing or development of new techniques
- Niche applications specific to burst mode

In summary: varied needs depending on type of experiment.

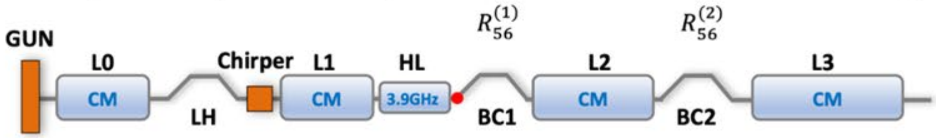
Ideally high repetition rate and high duty cycle machine with highly flexible beam distribution to accommodate these requirements.

Beam on demand for SRF based FELs

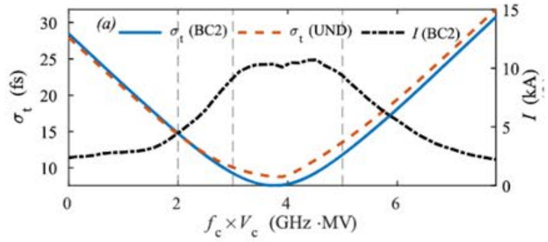
Zhen Zhang (SLAC)

To enhance the multiplexing of FEL facilities

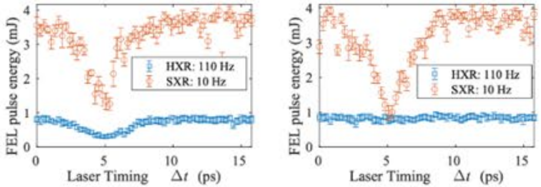
1. NC chirper cavity to control peak current, bunch length and energy chirp shot-by-shot at MHz repetition rate.

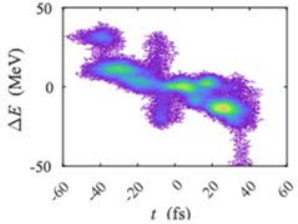


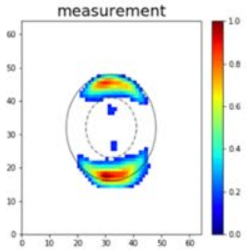
NC chirper cavity → CW mode → filling time < bunch spacing →zero-crossing phase
→ Vary induced energy chirp shot-by-shot



2. Selective laser heater shaping for produce attosecond at the LCLS-II





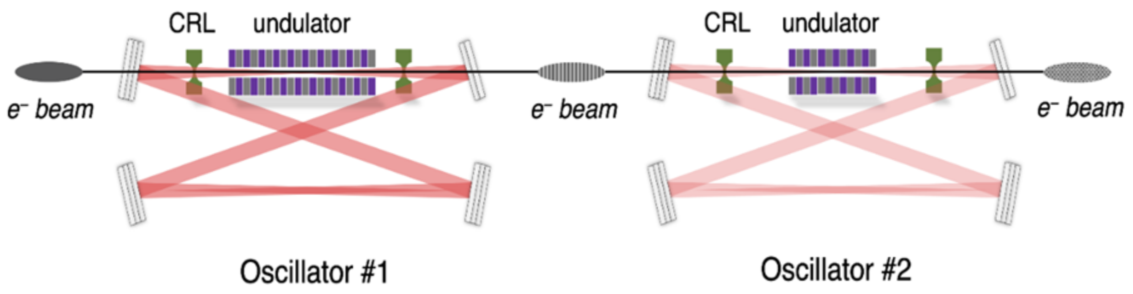


3. Multiplexed injector configuration to deliver low-emittance electron beams of different beam charges

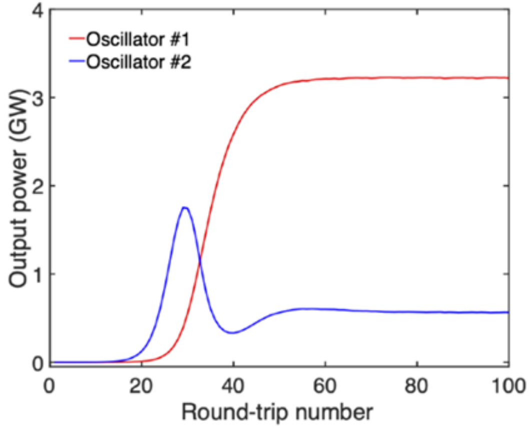
- Customized laser spot size for each charge is the most effective knob for this multiplexed configuration.

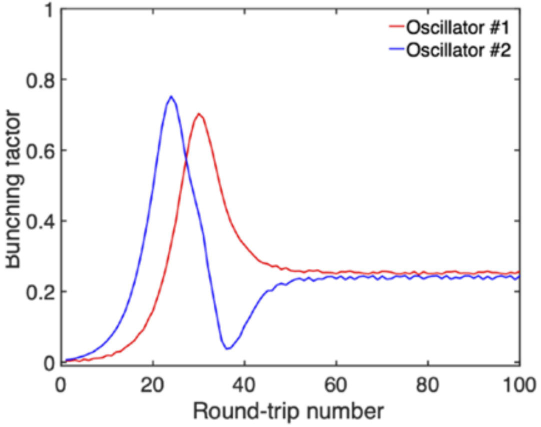
Multi-FELOs Driven by a Common Electron Beam
WE3A3, C.-Y. Tsai (HUST) & Y. Zhang (JLab)

Shape Outline



Name	Value	Unit
Resonant electron energy $E = \gamma_r mc^2$	5.7	GeV
Bunch length, rms σ_t	0.55	ps
Bunch charge	380	pC
Bunch current I_b	300	A
Normalized emittance ϵ_{nx}	0.3	μm
Energy spread σ_δ	0.3×10^{-4}	
Undulator period λ_u	1.88	cm
Number of undulator periods N_{u1}, N_{u2}	100/68	
Undulator parameter K	1.5	
Resonant wavelength λ_r	1.6	Å
Round-trip reflectivity R	0.8	
Outcoupling ratio α	0.04	





- Extend 1-D FEL model to study feasibility of two FELOs in serial connection
- The used e-beams seem still able to drive the second downstream oscillator
- The simulated output performances are still competent, compared with existing XFEL facilities
- The tandem-XFELO scheme inherits high rep-rate e-beam and thus increases total delivered photon flux

Summary

Zhen Wang (SARI-CAS)

- We report a new method for high repetition rate fully coherent pulse generation by taking fully advantages of the ERL and ADM.
- The proposed light source holds the merits such as fully coherent radiation with a brightness 5–6 orders of magnitude higher than that of a DLSR with the same beam energy, and much higher repetition rate comparing with an FEL.
- We also propose two future ERL light sources to generate fully coherent EUV and X-ray radiation, and consider a multi-point radiation emitting system consists of DBAs and radiators to support multi-user operation.
- However, limited by the photoinjector and the HOM BBU effect, the 100-mA-level average current is a big challenge. Meanwhile, dominated by the injector, the energy jitter, temporal jitter and the temporal stability might become larger than storage rings.
- The ADM technique has not been experimentally demonstrated yet, but a proof-of-principle experiment of ADM is under preparation at the Shanghai Soft X-ray FEL facility.

Summary

Sandeep Kumar Mohanty (DESY)

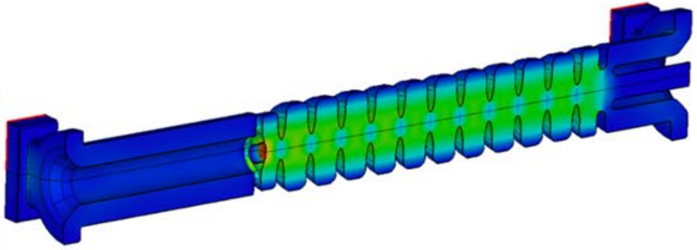
- **3 KCsSb** photocathodes were prepared at INFN LASA in July 2021 and successfully tested at PITZ **RF gun** [2].
  - ✓ High QE (**4-8 %** at 515 nm)
  - ✓ Thermal emittance (**0.6** mm.mrad/mm) (lower than Cs_2Te)
  - ✓ Response time (preliminary results show **< 100 fs**)
  - • Higher dark current than Cs_2Te
  - • Short operational lifetime (~48 hours)
- **To improve + optimize cathode recipe**: Two KCsSb cathodes (1 thick & 1 thin) have been produced with sequential deposition with **QE** @514 nm recorded **4-6** %.
- A new **"multi-wavelength" Optical Diagnostics** setup has been used during the cathode deposition
  - ✓ It gives information about real-time spectral response and reflectivity during cathode growth.
  - ✓ The optical spectra of these semiconductors provide a rich source of information on their electronic properties.
- Comparing the **spectral reflectivity** between two cathodes shows that **the intermediate phase**, i.e., K+Sb (**KSb** compound), and **the final phase**, i.e., **KCsSb** compound, potentially contain **different crystal structures** for **thick** (Sb = 10nm) and **thin** (Sb = 5 nm) cathodes. (Further verification through photoemission spectroscopy results is required!)
- By **comparing with DFT simulation data**, it has been found that, potentially, **both the cathodes** (i.e., thin and thick) have a **different band gap**.
- **Analyzing these optical spectra**, especially spectral reflectivity, and **comparing** them with the theoretical model **(DFT results)** offers a **valuable method to predict the electronic structure** of the grown compound.

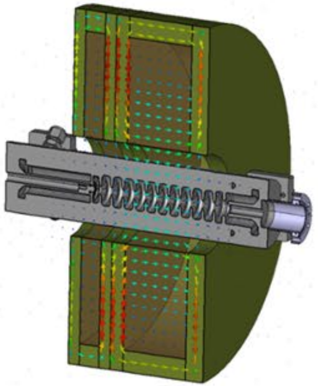
PAUL SCHERRER INSTITUT PSI

Travelling-Wave RF Photogun

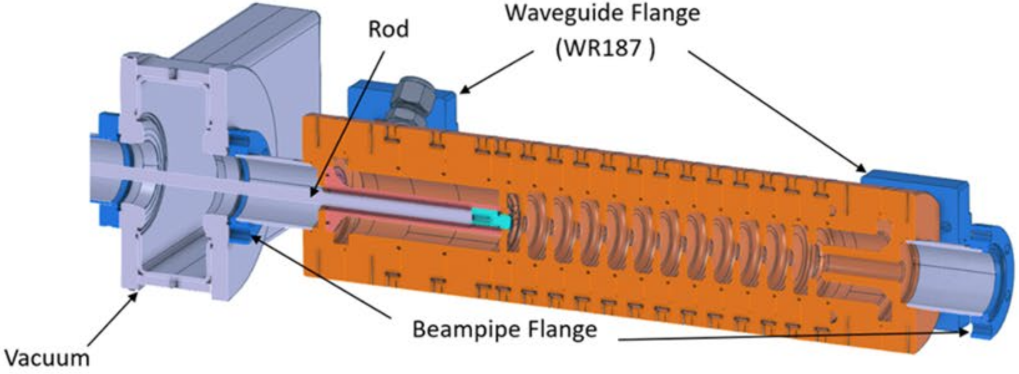
Thomas Geoffrey Lucas (PSI)

Electromagnetic design realised

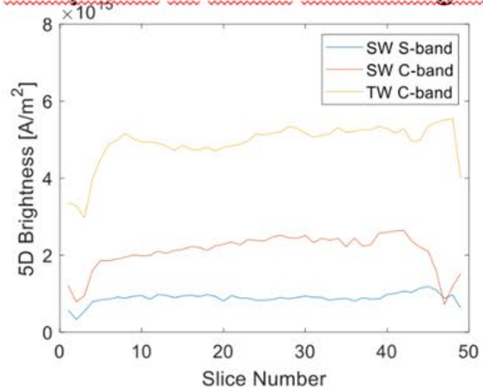




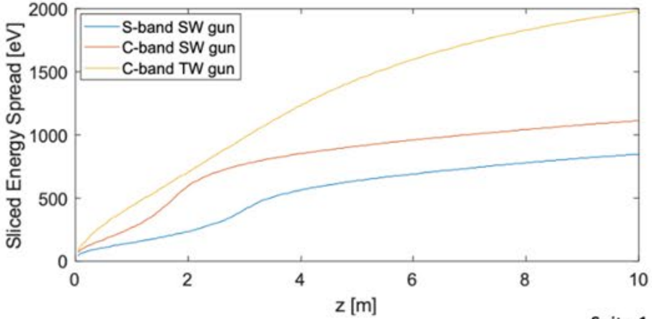
Mechanical design realised



Beam dynamics performed and compared to other technologies



Induced sliced energy spread (SES) though IBS illustrate slight increase in TW gun.

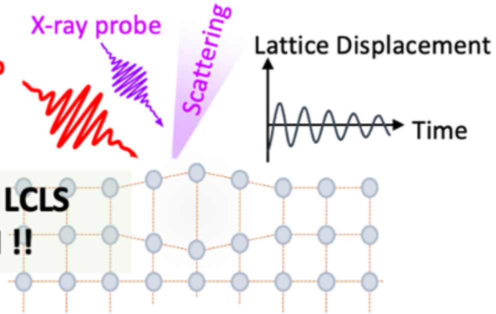


WE2 e-beam and FEL physics

An electron beam-based THz source and the transport of THz radiation over 120-150 meter distances for LCLS-II

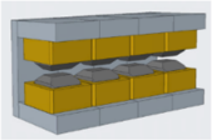
Meredith Henstridge, Alan Fisher, Matthias Hoffmann, and Zhirong Huang (SLAC)

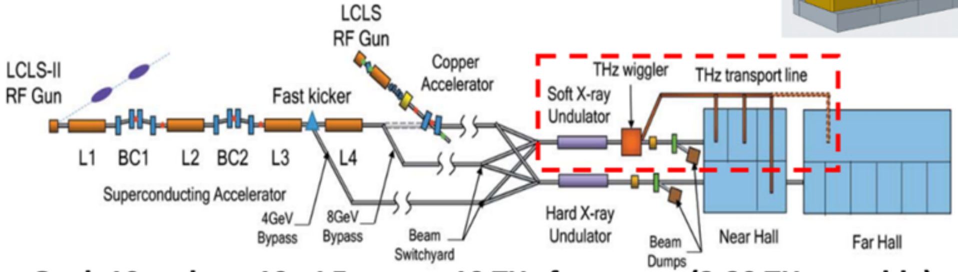
Which structural pathways and time scales lead to non-equilibrium phenomena driven by lattice vibrations?



Experiments at LCLS ... and LCLS-II !!

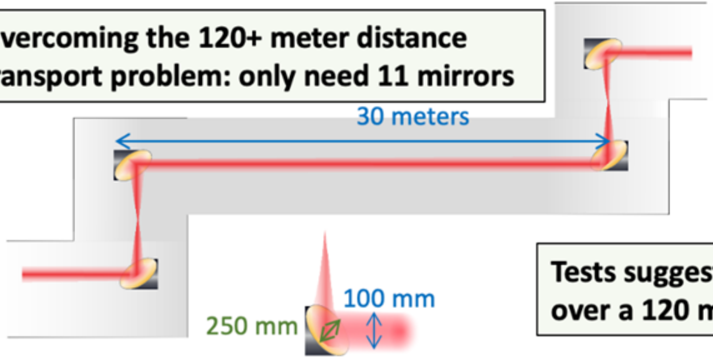
THz electromagnetic wiggler (collaboration with ANL)



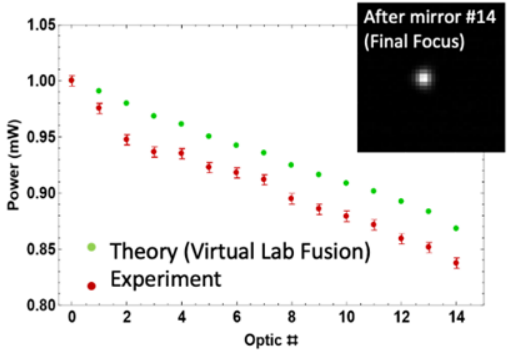


Goal: 10 cycles – 10 μJ Energy – 10 THz frequency (3-30 THz tunable)

Overcoming the 120+ meter distance transport problem: only need 11 mirrors

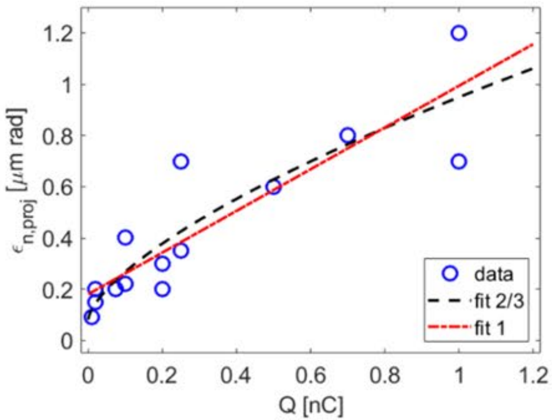


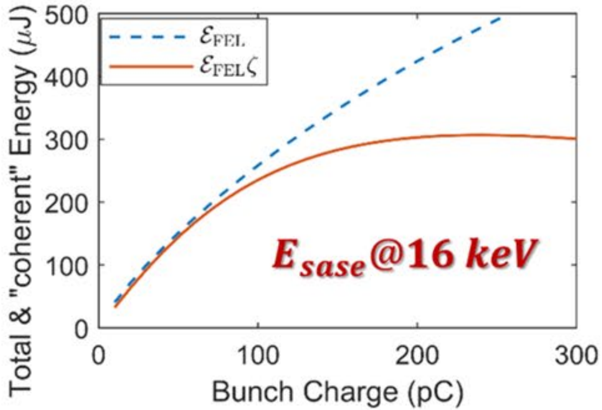
12-meter reduced scale setup indicates that losses are primarily ohmic at 1% per mirror at 30 THz



Tests suggest that the THz beam can be transported over a 120 meter distance with efficiency of 89%

Summary slide – WE2A4





- A semi-analytical estimate of $E_{sase}(Q)$ in the presence of slice and projected beam parameters is available, based on “invariant beam envelope” predictions at the injector and benchmarked collective effects.
- The model aims at highlighting dominant FEL dependences from “macroscopic” e-beam parameters.

An analytical method for longitudinal phase space backtracking (WE2A2)

- Motivation:
  - Increasing the peak current while producing “flat” current profiles and minimizing correlated energy spread is advantageous especially for FEL operation
  - Want to find longitudinal phase space (LPS) at some upstream point that gives a desired LPS downstream
  - Assume this upstream phase space can be obtained by additional manipulation further upstream i.e. tuning injector, shaping cathode laser, de-chirper, etc… taking advantage of lower beam power early in accelerator
- Approach
  - Develop analytical method for tracking LPS backwards to some upstream point in accelerator.
  - Consider current profile and chirp we want to track backwards as Nth order polynomials with endpoints S1 and S2:

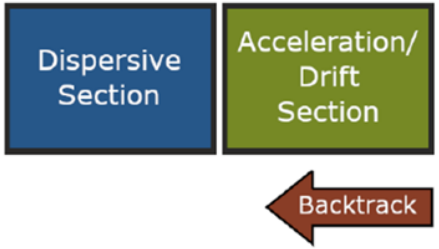
$$I_f(s_f) = I_{f0}(1 + I_{f1}s_f + I_{f2}{s_f}^2 + I_{f3}{s_f}^3 + \ldots + I_{fN}{s_f}^N) \quad S_1 < s_f < S_2$$

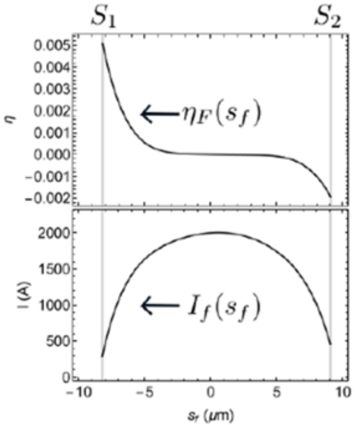
$$\eta_F(s_f) = h_{f1}s_f + h_{f2}{s_f}^2 + h_{f3}{s_f}^3 + \ldots + h_{fN}{s_f}^N$$

  - Break up accelerator into sections consisting of accelerator/drift section and upstream dispersive section
  - Find expressions for chirps acquired in accelerator/drift section to arbitrary polynomial order including collective effects
  - Track backwards to entrance of dispersive section. Repeat through next accelerator/drift and dispersive section. Solve for transformation of LPS and current profile at each step.
  - Assume LPS and current profile can be described as Nth order polynomials throughout **No fold over of LPS**

LCLS-II example case:

- Break up accelerator into 11 accelerator/drift/chirp and dispersion sections
- Track backwards from undulator entrance to laser heater exit
- Consider up to 6th order (and dispersion terms up to 3rd order)
- Free parameters: Linac phases, energy at various points, bunch compressor R_{56}’s etc…
- Generate 6-d phase space from backtracked LPS and forward track in Elegant to compare
- Collective effects: Longitudinal space charge (LSC), cavity wakefields, resisitive wall wakefields and coherent synchrotron radiation (CSR)





SUMMARY AND CONCLUSIONS

- We have developed quantum theory of XFEL-pumped ASE including seed field and 3D effect in paraxial approximation
- Assuming factorization: $\left\langle \sigma_j^a(\tau)\sigma_k^b(\tau)\right\rangle = \langle \sigma_k^a(\tau)\rangle\left\langle \sigma_k^b(\tau)\right\rangle$, $a \neq b$, the theory can be cast in the form of a modified MBEs, in which a noise term is added to the atomic coherence
- An efficient simulation code was developed based on the modified MBEs.
  - The effective initial noise is higher in 3D than in1D
- Since seed field is included, a multi-pass XLO can be simulated
- The performance for hard X-ray XLO may be limited due to ultrafast spontaneous emission

- ***We thank Nina Rohringer, Andrei Benediktovitch, Linda Young, and Kai Li for discussion***