67th ICFA Advanced Beam Dynamics Workshop on Future Light Sources (FLS 2023), Lucerne, Switzerland, from 27 August to 1 September 2023

Working Group C: Compact Light Sources

Conveners: Massimo Ferrario/ LNF, Masaki Kando/ QST, Yen-Chieh Huang/ NTHU

Prepared by Yen-Chieh Huang & Philippe Piot

Presented Size of Accelerator/Light source

https://www.indiatimes.com/auto/electric/toyota-ultra-compact-battery-electric-car-unveiled-378075.html

~ meters

https://www.carousell.sg/p/swiss-made-chrono-watch-1174083124/

~ centimeters

https://www.freepik.com/free-photos-vectors/virus-cartoon

~ nanometers

Compact Light Sources based on

- Inverse Compton Scattering
- Laser plasma accelerator (LPA)
- Others – Two-beam accelerator, dielectric laser accelerator, electron-driven nano-structures

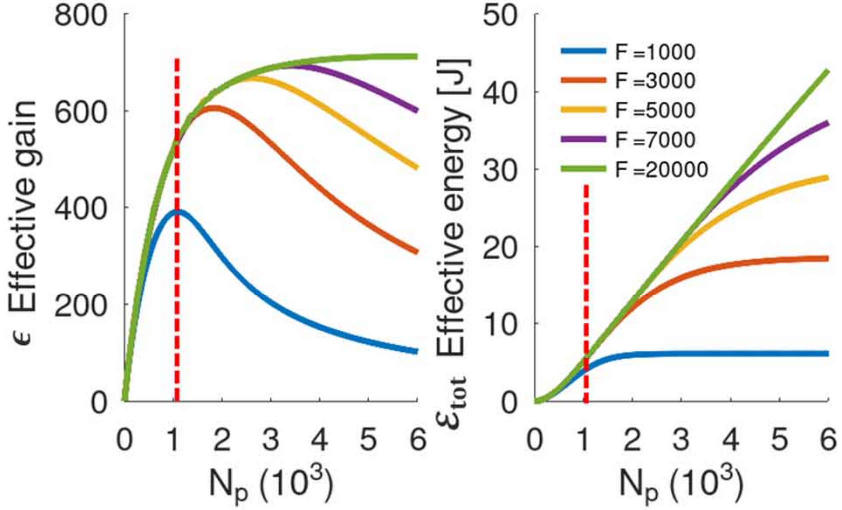
# of papers:~ 20

- Inverse Compton Scattering

TU1C1

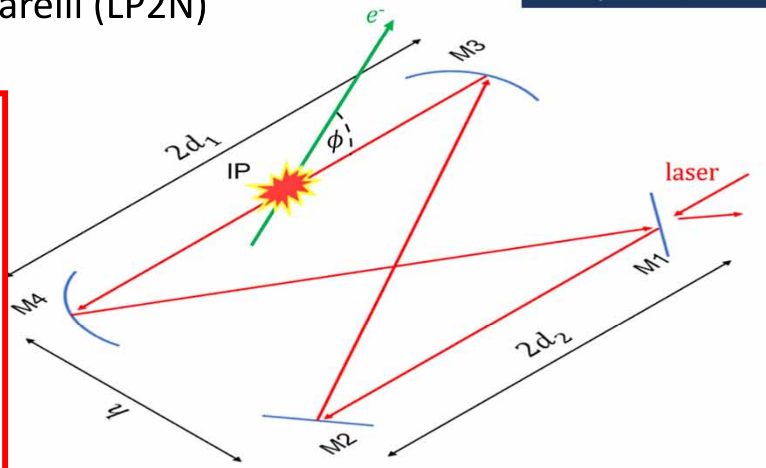
An efficient Optimisation of a Burst Mode-Operated Fabry-Perot Cavity for Compton Light Sources

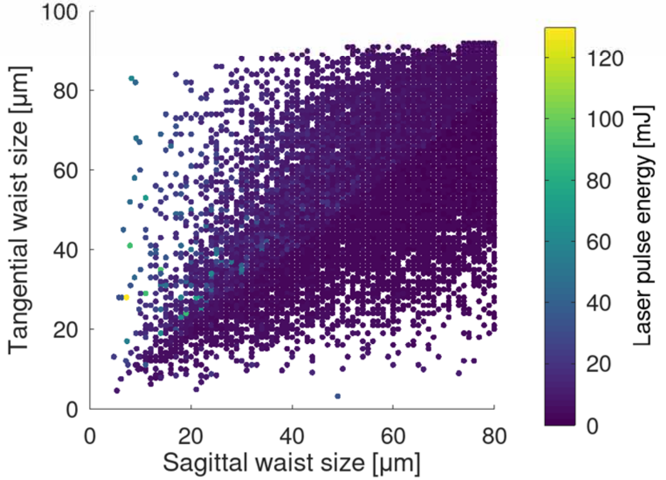
Vlad Mușat, Andrea Latina, Eduardo Granados (CERN), Eric Cormier, Giorgio Santarelli (LP2N)

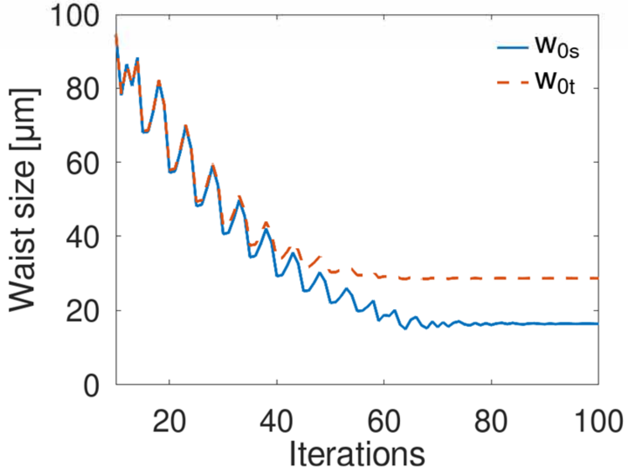


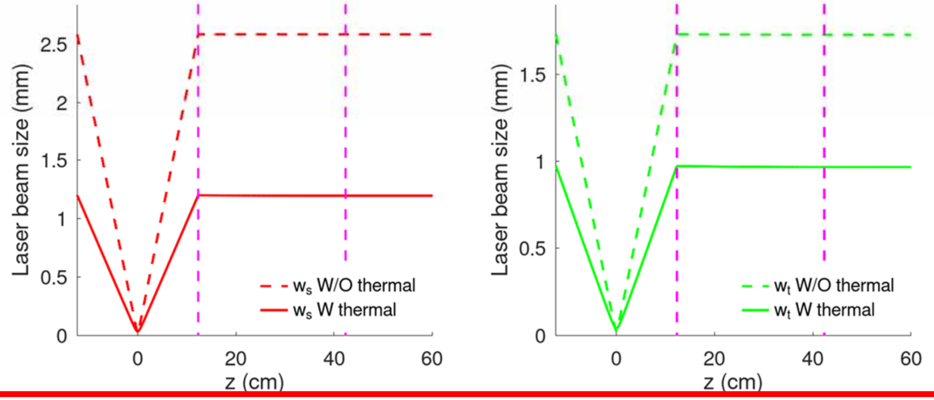
Significant improvements were made for the optimisation of a burst-mode operated Fabry-Perot cavity for ICS.

Burst parameters optimisation: By maximising the effective energy of the cavity, a 40% increase in the total flux can be obtained (wrt maximising ϵ)







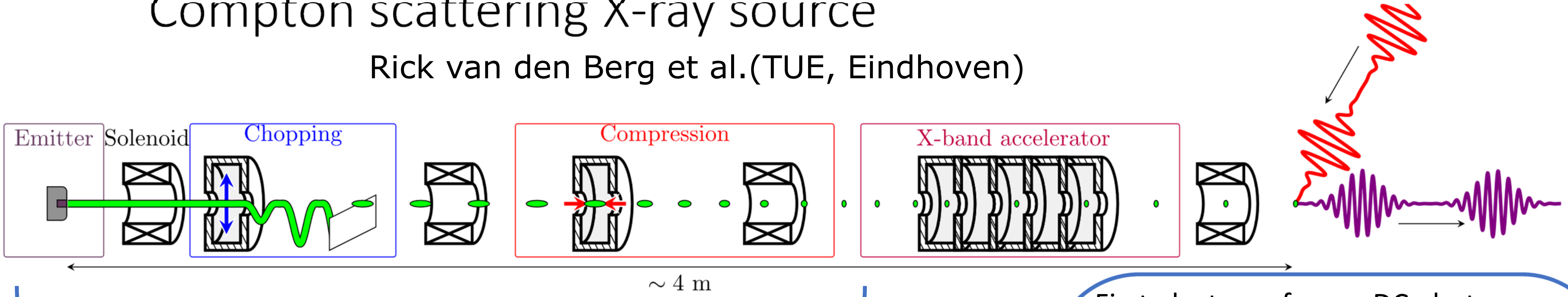


Geometry optimisation: By using the simplex algorithm, the computation runtime was reduced by more than four orders of magnitude. Thermal lensing was implemented.

TU4P38

Burst mode operation in the Smart*Light inverse Compton scattering X-ray source

Rick van den Berg et al.(TUE, Eindhoven)

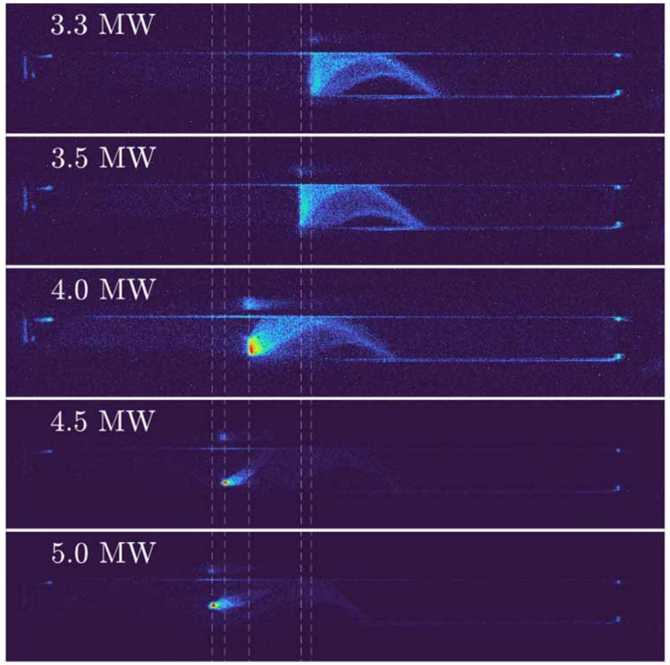


High repetition rate (1.5 GHz) electron injector

The burst mode operation target beam parameters.

	Low Current	High Current
Emission current	10 mA	90-160 mA
Repetition rate	1.499275 GHz	1.499275 GHz
Burst length	200 ns	200 ns
Charge per bunch	2 – 3 pC	20 – 50 pC
Bunch length	< 2 ps	<2 ps
Transverse emittance	40 – 100 nm rad	400 – 1200 nm rad

First electrons from a DC photogun accelerated by the X-band structure



By combining a high rep. rate gun and an Fabry-Perot cavity the x-ray production in the Smart*light setup can be increased significantly.

Rick van den Berg – r.g.w.v.d.berg@tue.nl

MO4C3

Generation of GeV Photon Energy at European X-Ray Free Electron Laser

Illya Drebot et al.

This study theorizes the possibility of generating quasi-monoenergetic gamma photons at energies of 2.8 GeV and 4.6 GeV with low energy resolutions (0.005 and 0.01 BW), and the potential to reach up to 6 GeV using Inverse Compton scattering with a 14 GeV (up-to 17 GeV) electrons at EuXFEL. Two possible laser systems for achieving high luminosity are being considered. Additionally, the specific pulse structure at EuXFEL and repetition rate have been taken into account.

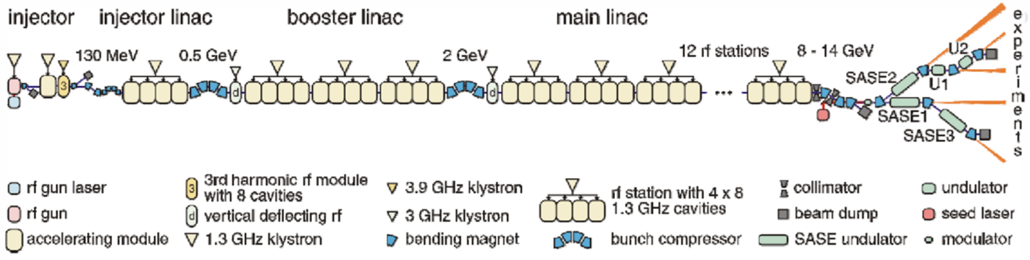
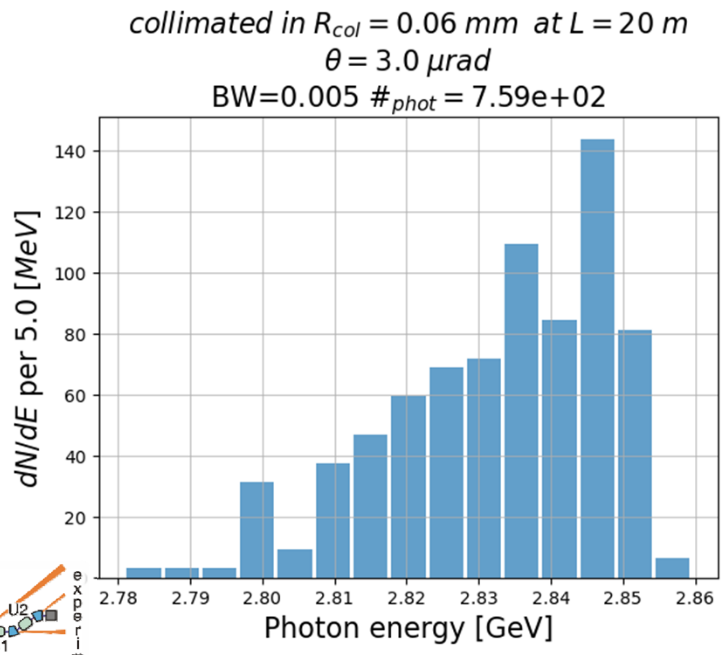


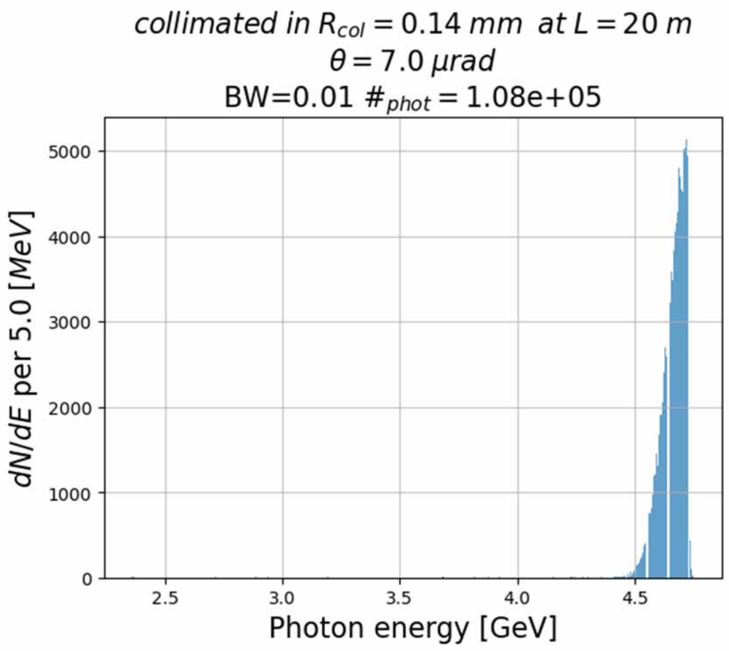
Figure 1: Schematic layout of the European XFEL complex, the third harmonic system is at the injector stage.

E_{las}=1.2 eV (1030 nm). PulseE=2.7 mJ



$\#_{phot}$ per sec =2*10^7 (for 27 kHz)

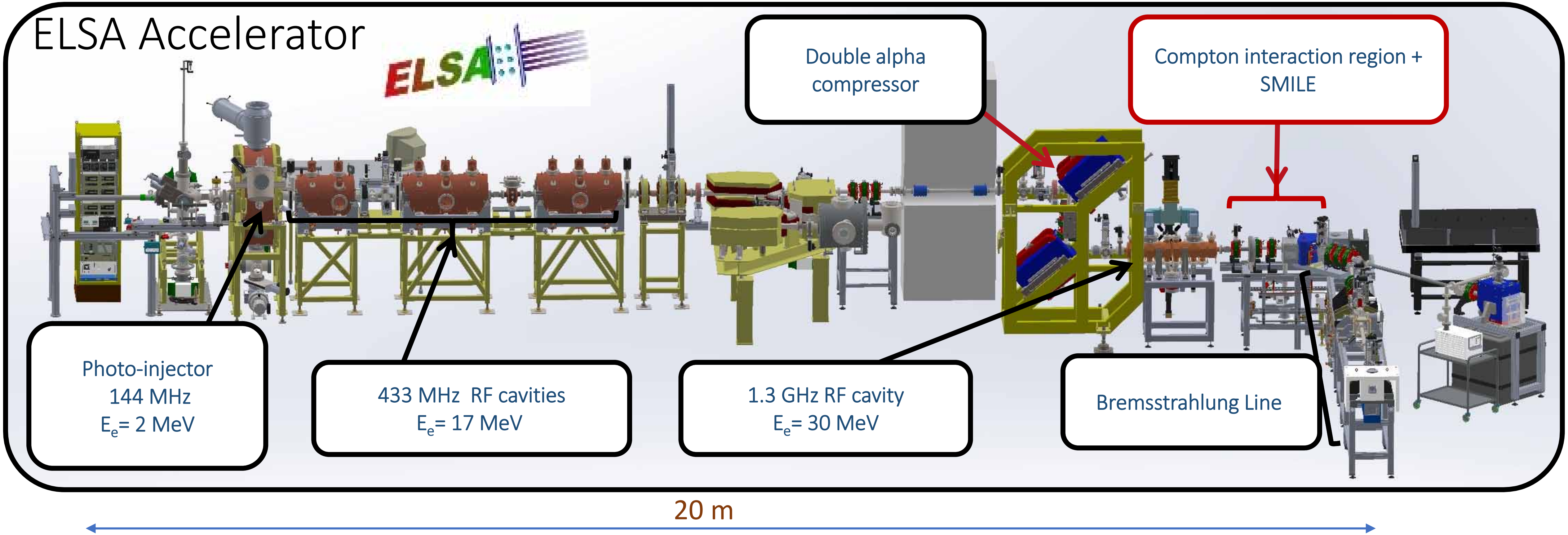
E_{las}=2.4 eV (515 nm). PulseE=0.2 J



$\#_{phot}$ per sec =3.4*10^7 (for 320 Hz)

illya.drebot@mi.infn.it

Inverse Compton Scattering X-ray Source of the ELSA Accelerator (CEA DAM, France) • **Abel PIRES (CEA DAM, LMCE)**



Typical bunch charge : 0.1 – 3 nC
Bunch duration : 15 – 100 ps
1 – 10000 bunches per train (1 – 5 Hz)
Emittance : 2 – 30 µm

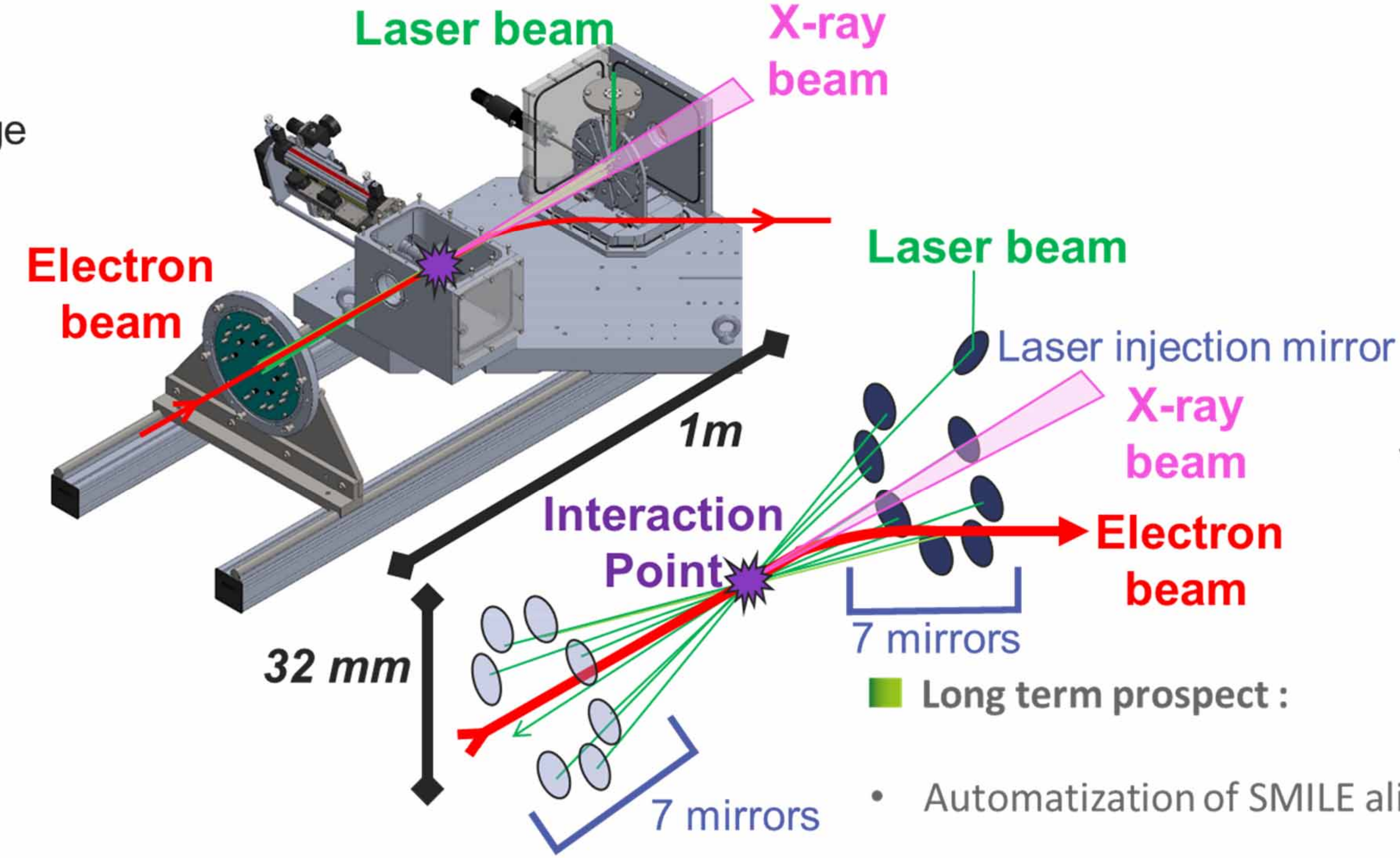
The Inverse Compton X-ray Source at ELSA

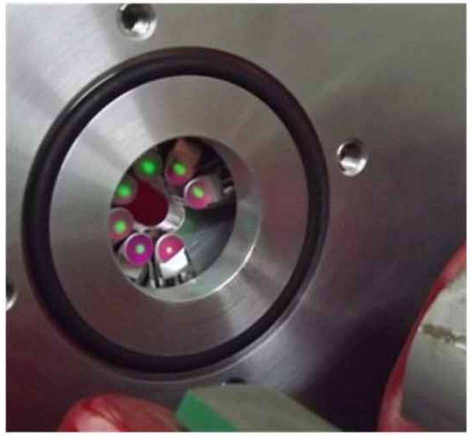
3D view of the interaction point and SMILE device

- **Abel PIRES (CEA DAM, LMCE)**

SMILE :

Système
Multi-passage
Interaction
Laser
Electron





View of the laser impacting the mirrors surfaces

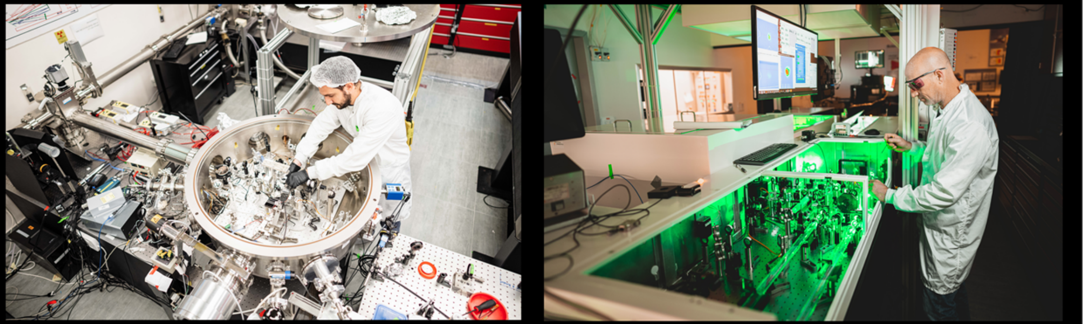
Long term prospect :

- Automatization of SMILE alignment
- Studies under way for an upgrade, including new 1.3 GHz cavity/klystron/modulator.

- **On-going optimization for interaction area, laser, electrons**
- **Compton source experiments on ELSA : dec 2023 – Feb 2024**

TU1C3

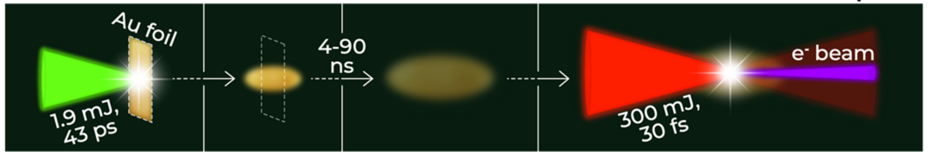
Plasma Guided Compton Source



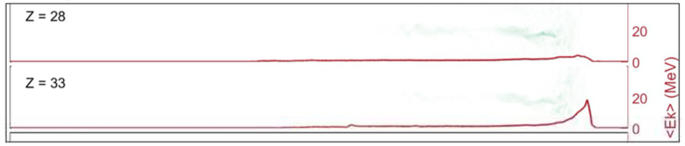
Ishay Pomerantz
The School of Physics and Astronomy, Tel Aviv University

NePTUN
Nuclear Photonics
at Tel-aviv University
research group

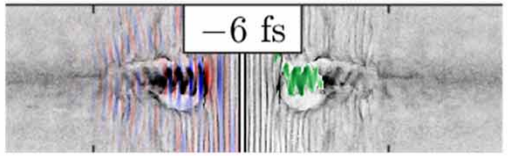
- Direct laser acceleration - Efficient conversion of eV photons to MeV electrons



- Target's atomic number must be matched with the laser intensity for efficient acceleration



- A bright Compton source formed by two DLA channels (PIC study)



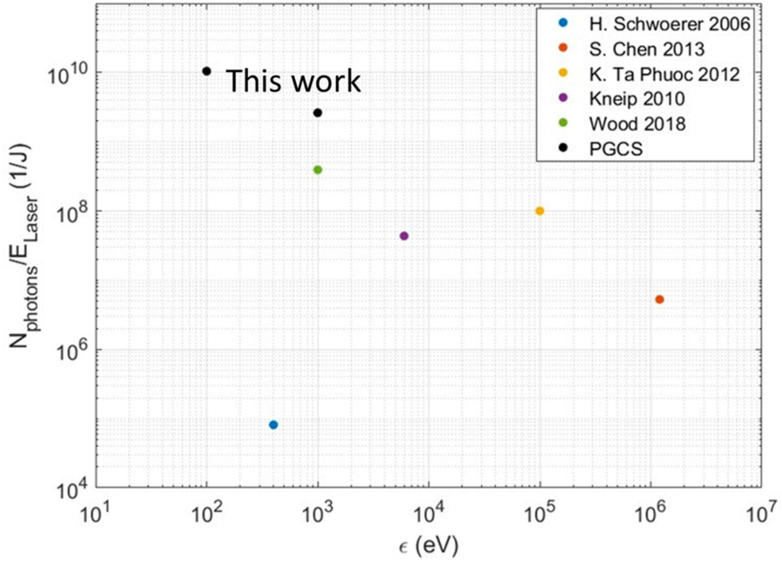
1J / 30 fs laser:

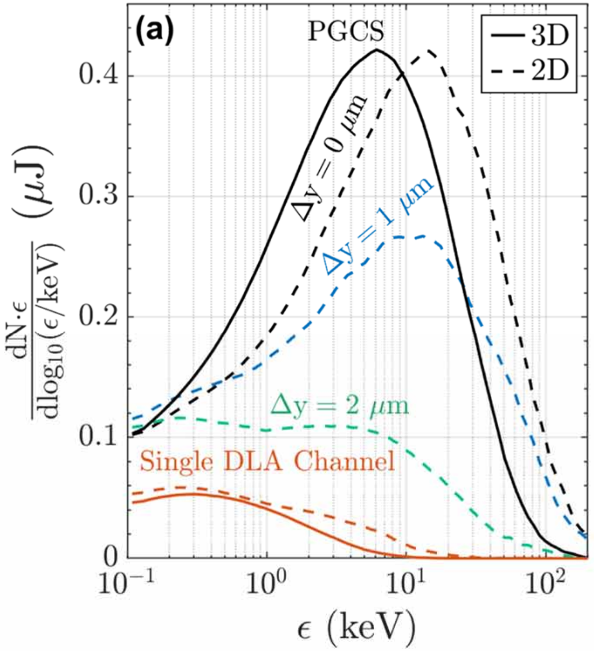
~5 KeV photons

10^{23} photons/ s mm^2 mrad^2 1% BW

- 2024: Experimental realization at TAU

High conversion efficiency





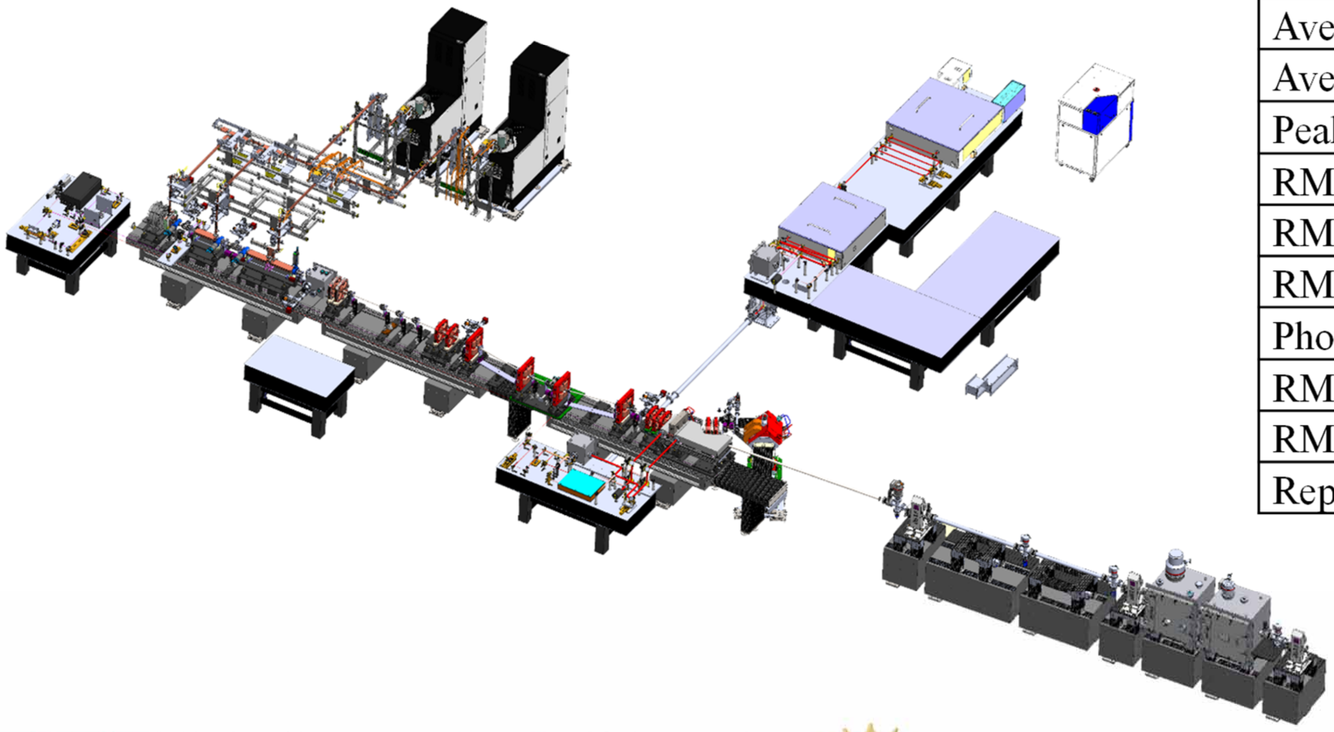
TU1C4

William Graves
Biodesign Institute and CISA
Arizona State University

CXLS

Phase 1 Hard X-ray ICS Source

Built and now commissioning.
First x-rays Feb 2, 2023



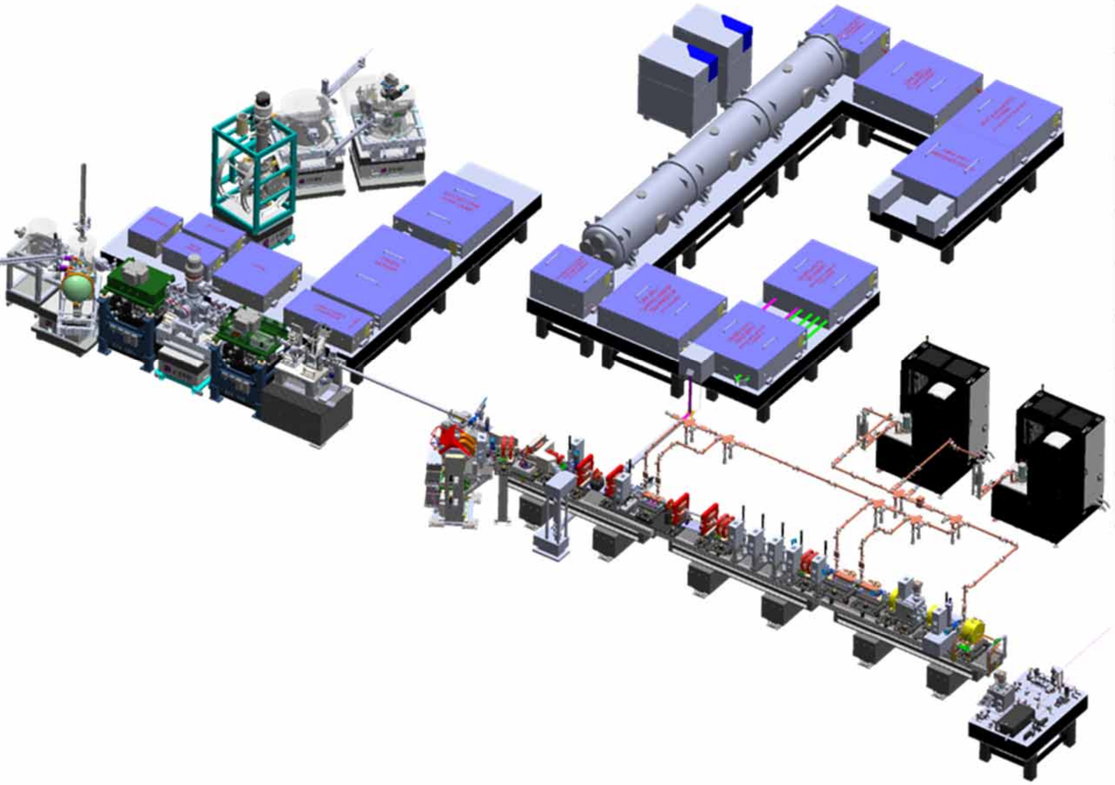
Parameter	0.1% Bandwidth	5% Bandwidth
Photon energy range (keV)	2 – 20	2 – 20
Average flux (ph/s)	$5x10^{9}$	$1x10^{11}$
Average brilliance*	$2x10^{12}$	$5x10^{12}$
Peak brilliance*	$3x10^{19}$	$9x10^{18}$
RMS source size (um)	3.0	3.0
RMS opening angle (mrad)	4.0	4.0
RMS vertical angle	4.0	4.0
Photons per pulse	$5x10^{6}$	$1x10^{8}$
RMS pulse length (fs)	<300	<300
RMS timing jitter	<100	<100
Repetition rate	1000	1000

*Brilliance units are photons/(s .1% mm^{2}mrad^2)

CXFEL

Phase 2 Soft X-ray Coherent Laser

5 year construction began March 2023
under $90.8M NSF midscale RI-2 award



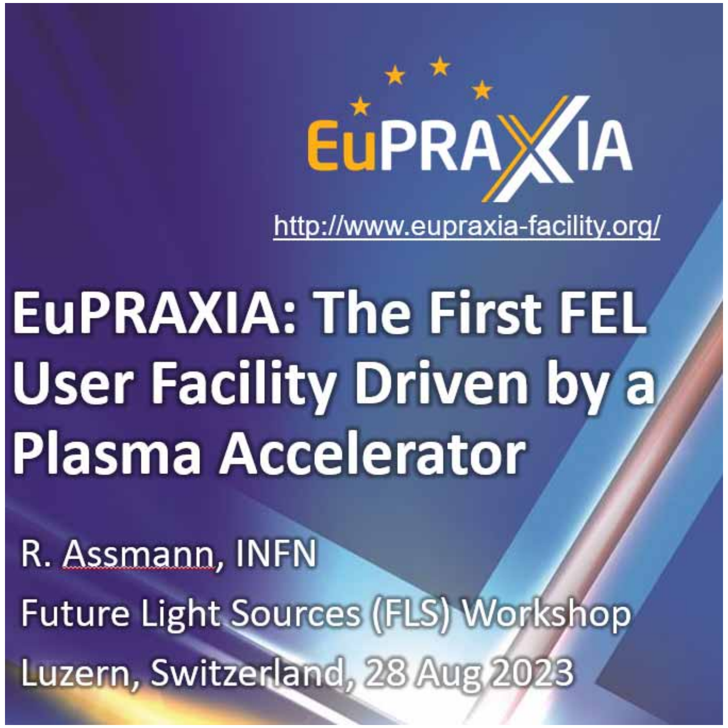
Design Performance

Photon energy (eV)	250	1000	2500
X-ray wavelength (nm)	4.9	1.2	0.49
Average flux at 1 kHz (ph/s)	8.0E+11	1.1E+11	4.4E+10
Average brilliance*	1.3E+15	1.2E+16	7.3E+16
Peak brilliance*	1.2E+28	5.6E+28	1.4E+29
RMS source size(um)	0.9	0.5	0.3
RMS source divergence (urad)	440	188	117
X-ray flux per shot – energy (nJ)	32	18	18
Photons per pulse	8.0E+08	1.1E+08	4.4E+07
Pulse length FWHM (fs)	9.1	4.6	1.9
Bandwidth FWHM (%)	0.18	0.09	0.08
RMS timing jitter (fs)	<10	<10	<10
Repetition rate	1000	1000	1000
Electron beam energy (MeV)	14	29	46

*Brilliance units are photons/(s .1% $mm^2 mrad^2$)

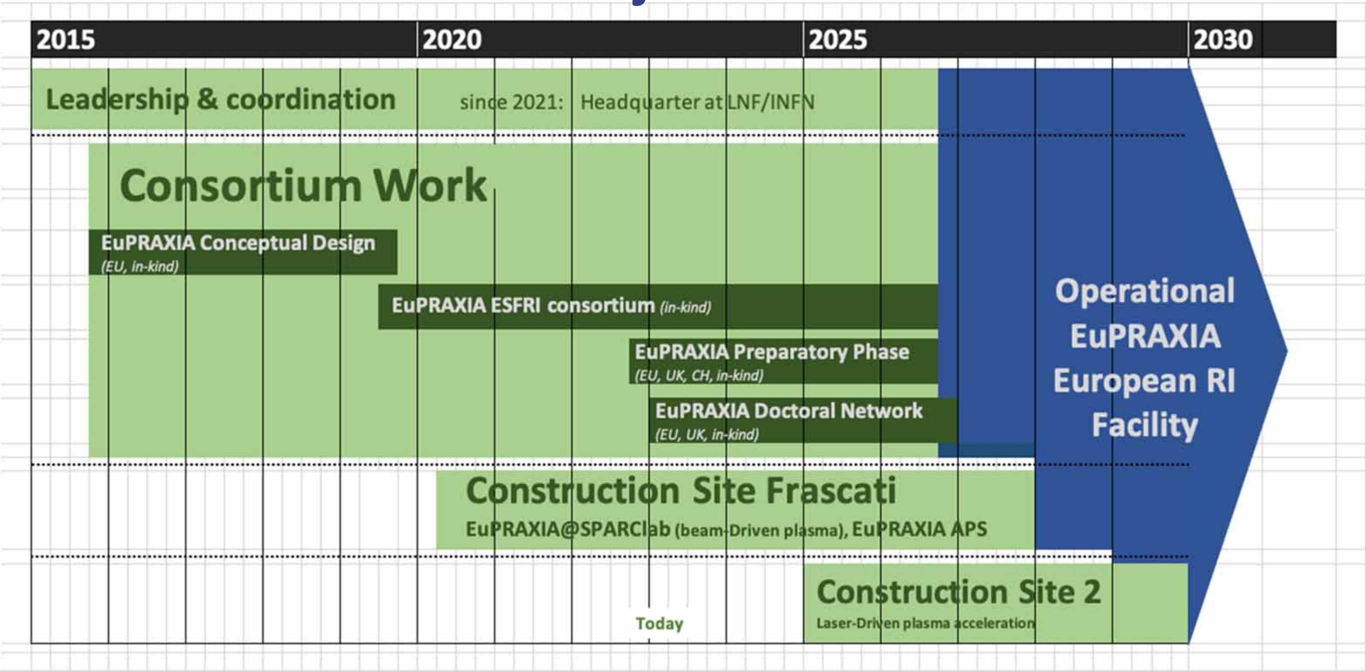
- Laser-plasma accelerator

MO1L1



- EuPRAXIA is a design and an ESFRI project for a distributed European Research Infrastructure, **building two plasma-driven FEL´s in Europe**.
- EuPRAXIA FEL site in Frascati LNF-INFN is sufficiently funded for **first FEL user operation in 2028**.
- Second EuPRAXIA FEL site will be selected in next 18 months, among **4 excellent candidate sites**.
- Concept today **works in design and in reality**. Expect (solvable) problems in stability for **24/7 user operation**. Facility needed to demonstrate!

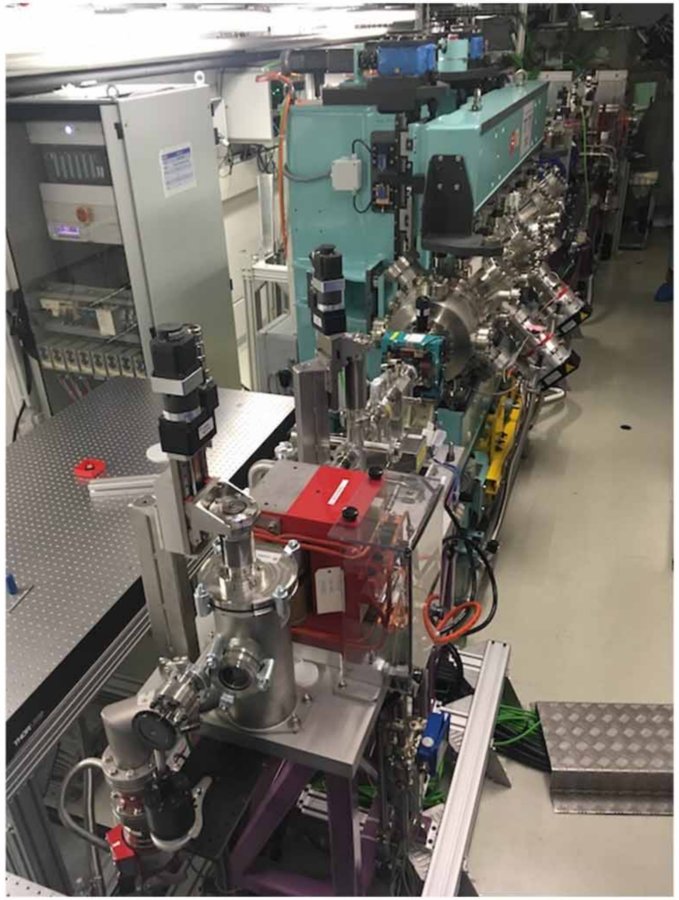
EuPRAXIA Project Timeline



TH2C1

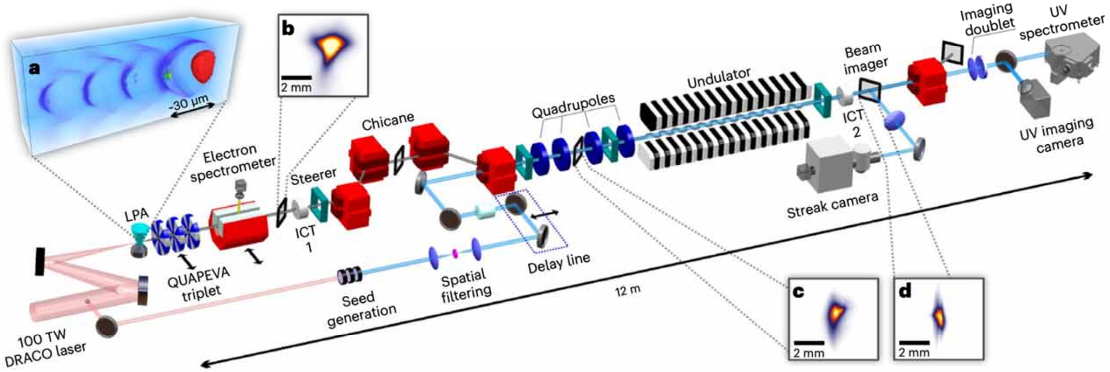
The COXINEL seeded Free Electron Laser driven by the Laser Plasma Accelerator at HZDR
Collaboration SOLEIL/HZDR/LOA/PhLAM

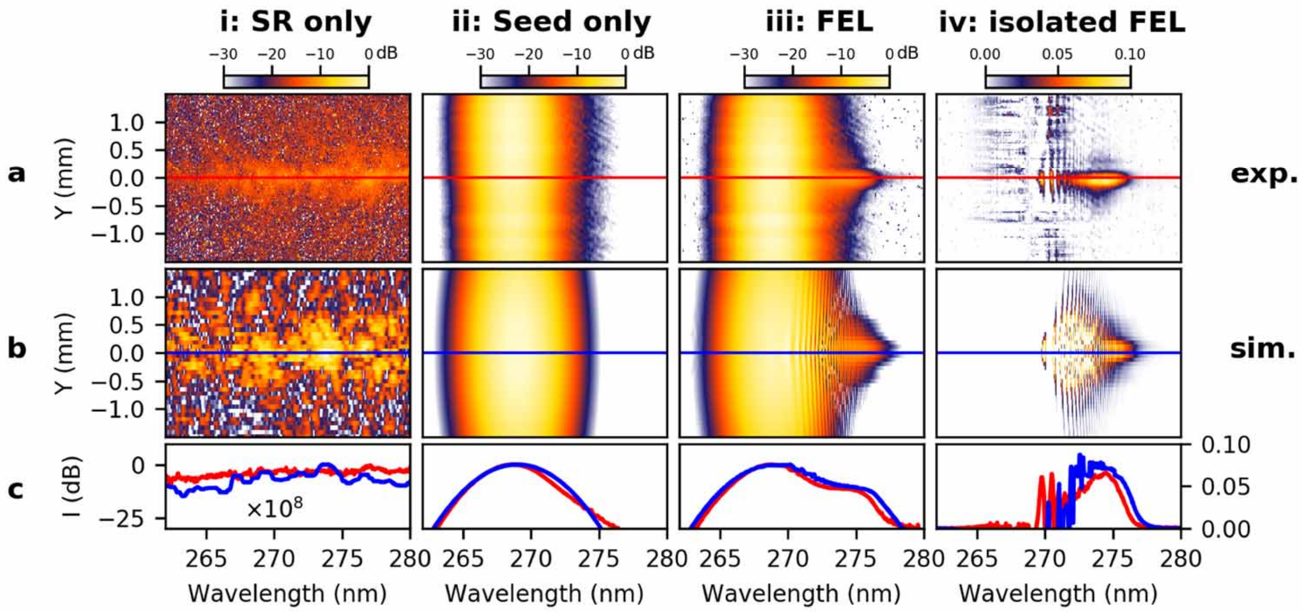
Presented by Marie E. Couprie



100 TW–class arm of IR DRACO laser

188 MeV ± 6 MeV
213 ±13 pC
RMS relative energy spread : 6.3 ± 0.8%
FWHM charge density: 6.3 ± 1.3 pC/MeV
H. divergence: 0.8 ± 0.2 mrad within 180-198 MeV
FWHM duration : 14.8 ± 1.6 fs





M. Labat, J. Couperus, A. Ghaith, A. Irman et al., Nature Photonics, 1-7 (2022)

TH2C2

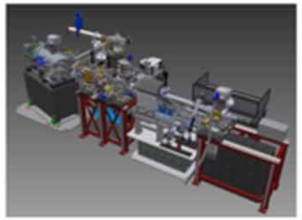
- **Technologies are ready for the PHASE0-commissioning at ELI-Beamlines**
- **'Water-window' incoherent undulator radiation will be generated for users after commissioning of the PHASE1, utilizing a novel high-repetition rate (up to 50 Hz) high-power L2-laser system**

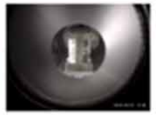
Development of Laser-Driven Plasma Accelerator Undulator Radiation Source at ELI-Beamlines

Alexander Yu. Molodozhentsev (Eli-Beamlines, Prague, Czech Republic)

○ LPA-based Incoherent Undulator Radiation Source

PHASE-0
Q4-2023



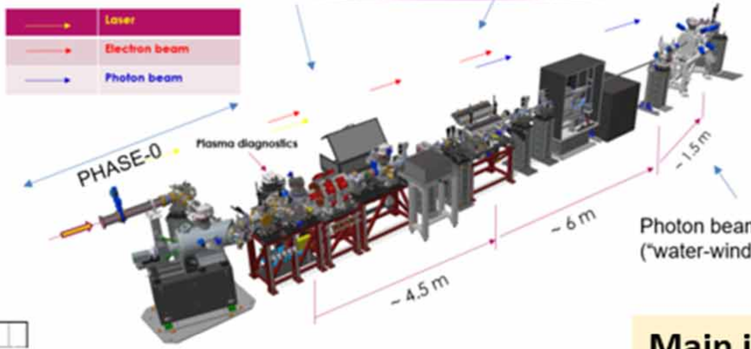


Electron beam spectrometer and dump

Compact Undulator

Electron beamline

PHASE-1
2024



Photon beamline
("water-window" photons)

Undulator parameters

Undulator period	mm	5
Number of period		100
Total length	mm	500
On-axis magnetic field	T	0.6
K-value		0.28

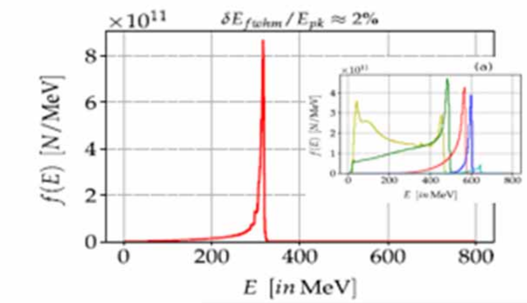
L2-DUHA laser system (in collaboration with STFC/UK)

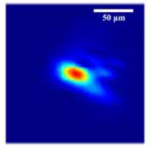
Photon beam parameters (PHASE#1) / Estimation

		W_e = 300 MeV / Q_b=30pC	W_e = 600 MeV / Q_b=30pC
Photon energy (1st harmonic)	eV	165	658
Photon wavelength (1st harmonic)	nm	7.5	1.8
Number of photons (0.1%bw)		1.7×10^5	7.1×10^6
Peak Brilliance (at peak current of electron bunch)	*	4.8×10^{20}	1.9×10^{21}
Effective beam size and divergence of the photon beam (1st harmonic)			
$\Sigma x,y$	μm	114	114
$\Sigma x',y'$	mrad	0.087	0.043

* photon/sec/mrad²/mm²/0.1%bw

Optimization of staged-LPA





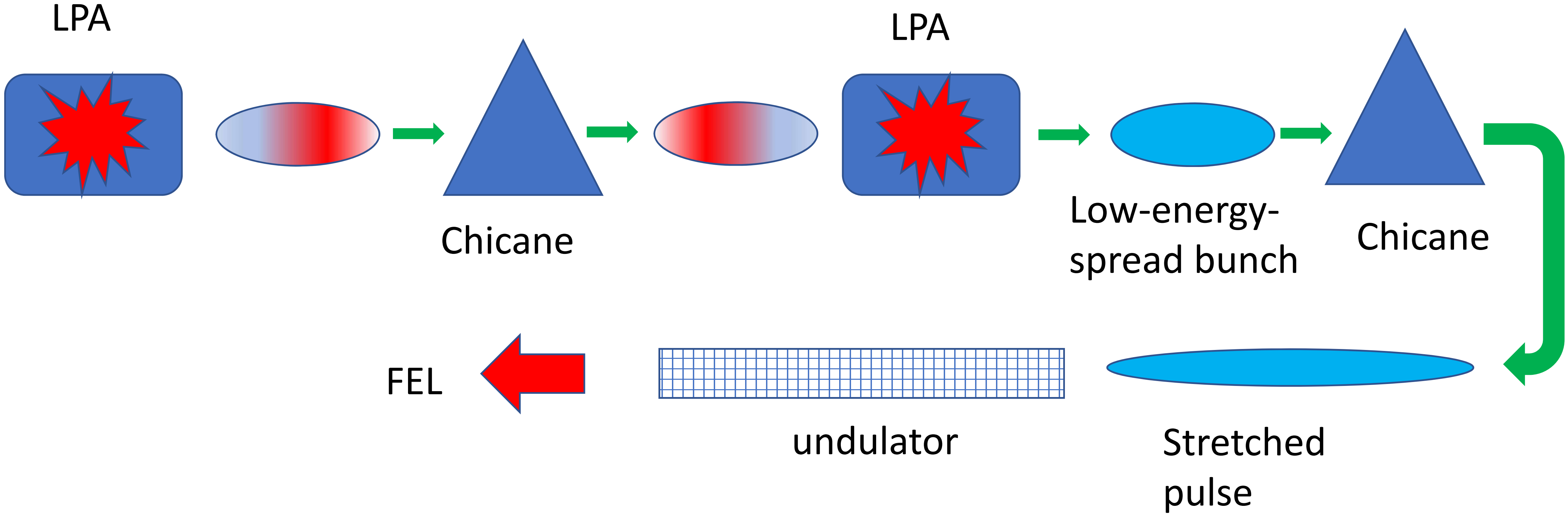
L3-laser beam in focus

Main issues:
- High repetition rate (from 25 Hz up to 50 Hz), utilizing the L2-DUHA laser
- Stable and repeatable operation
- Improvement of the LPA-based electron beam quality
- Electron @ Photon beam diagnostics

TH2C3

A Novel X-ray Free-electron Laser Scheme Based on Cascaded Laser Wakefield Accelerators

Fei Li (TUB, Beijing)

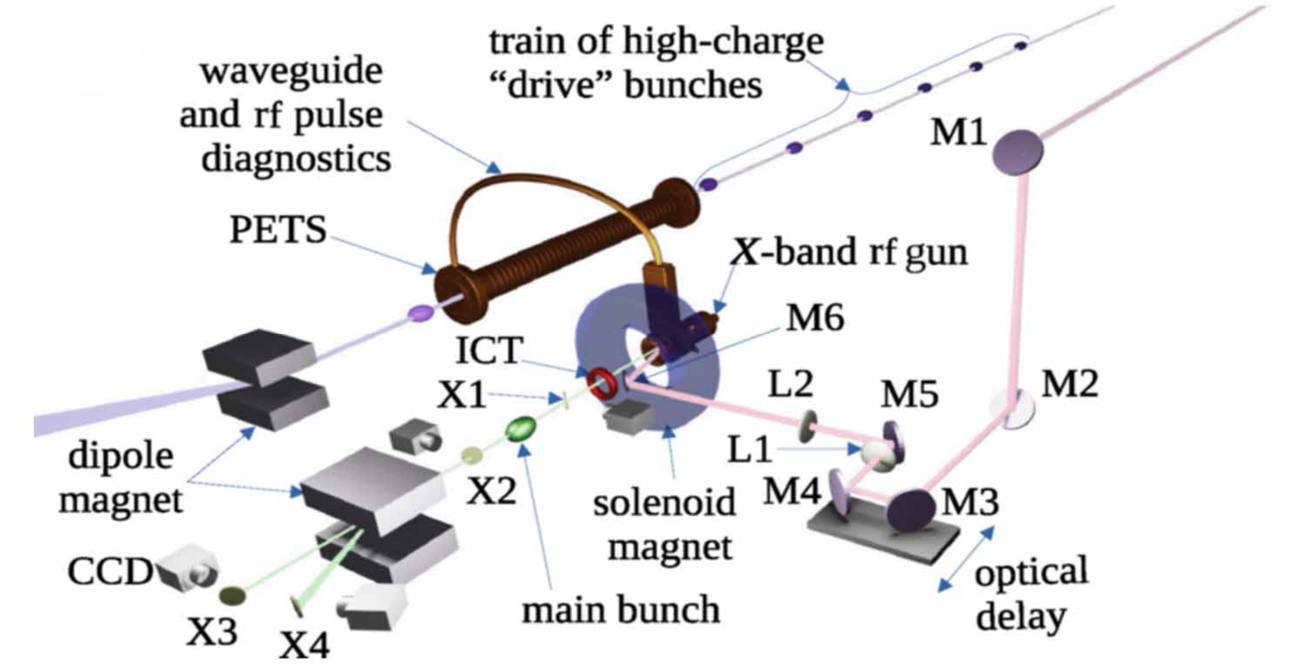


- Others – Two-beam accelerator, XFEL pumped x-ray laser, dielectric laser accelerator, electron-driven nano-structures

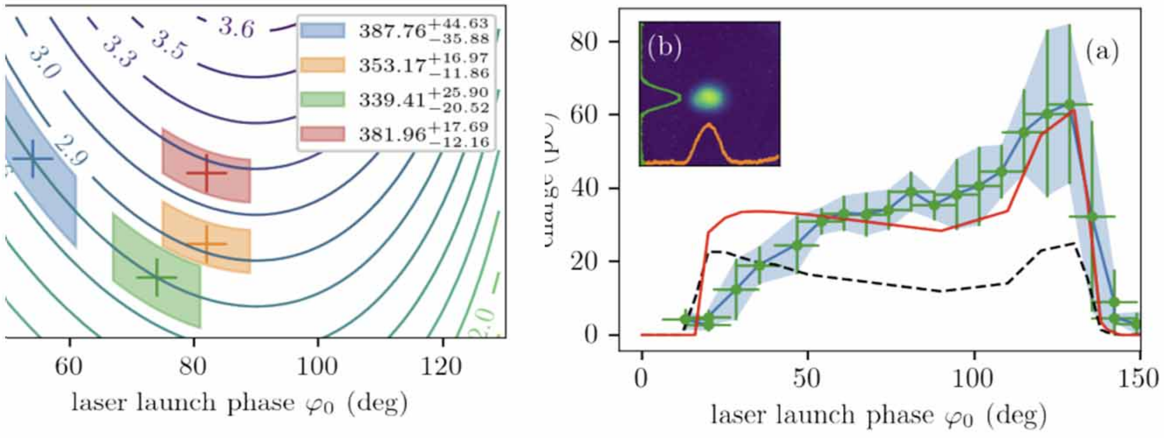
TWO-BEAM ACCELERATION FOR COMPACT FELS

Philippe Piot, Argonne National Laboratory, Northern Illinois University

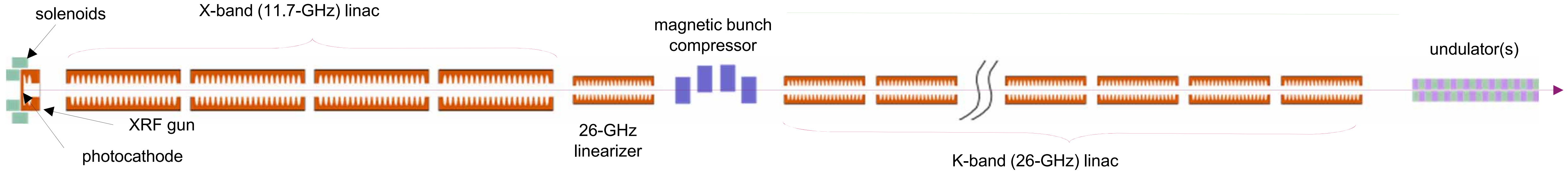
Stable operation at high field



nonstrated 400 MV/m surface field on photocathode
X-band RF (XRF) gun



veloping a TBA concept for a V/EUV
FEL driven by a 500-MeV TBA

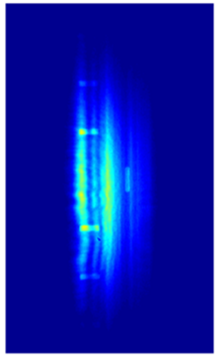


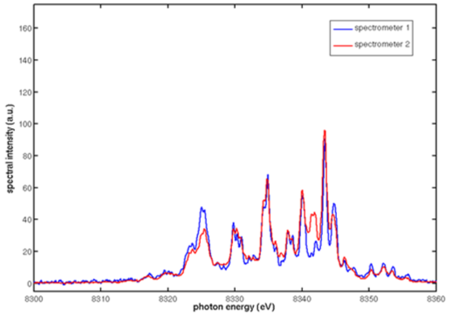
W.H. Tan, et al. 10.1103/PhysRevAccelBeams.25.083402 (2022)

WE2C1

Population Inversion X-ray Laser Oscillator at LCLS and LCLS-II

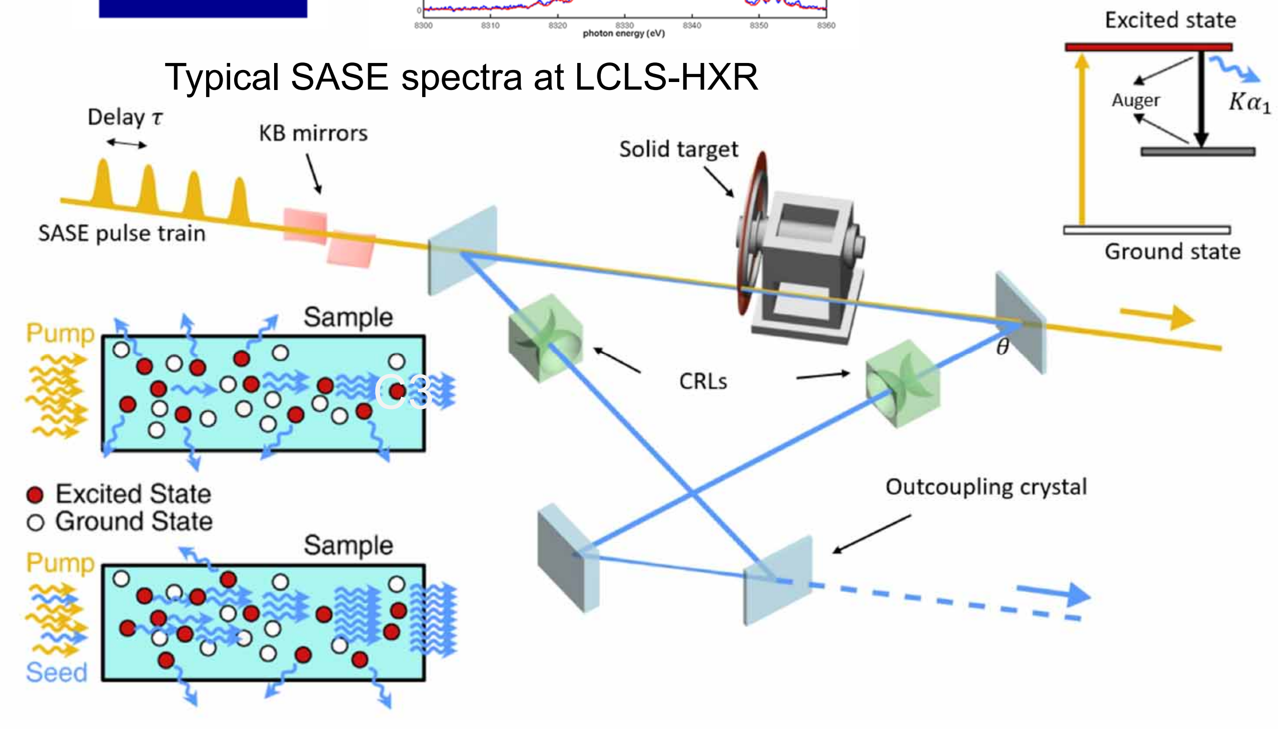
Alex Halavanau, on behalf of XLO collaboration





A solution to the unstable SASE

Typical SASE spectra at LCLS-HXR



XLO cavity first prototype at LCLS-CXI end-station

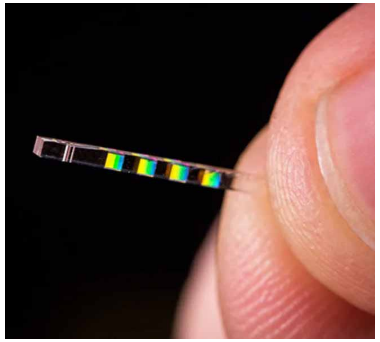
- Based on inner-shell population inversion (can be accomplished with an XFEL pump, yes, still need an XFEL)
- Low intensity (several uJ)
- 10-50 fs long, transform limited
- No wavelength jitter due to laws of QM
- PoP: 8 keV Cu K alpha1

MO4C1

Average brilliance of Coherent Undulator Radiation driven by Dielectric Laser Accelerator is comparable to 3rd-generation light sources in the VUV/EUV/soft-x-ray spectrum (due to high bunch rate + nano-bunch superradiance)

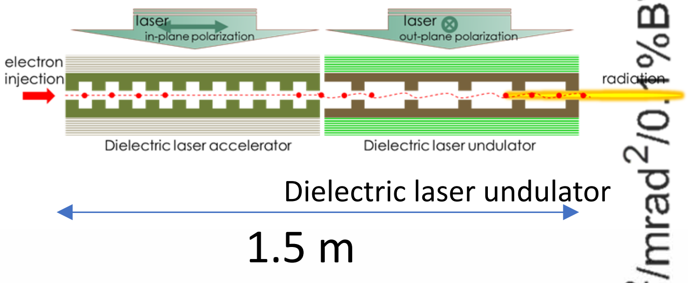
Y. C. Huang of NTHU & R. L. Byer of Stanford U.

Sub-GW ~ GW circulating power (Taiwan photon source)

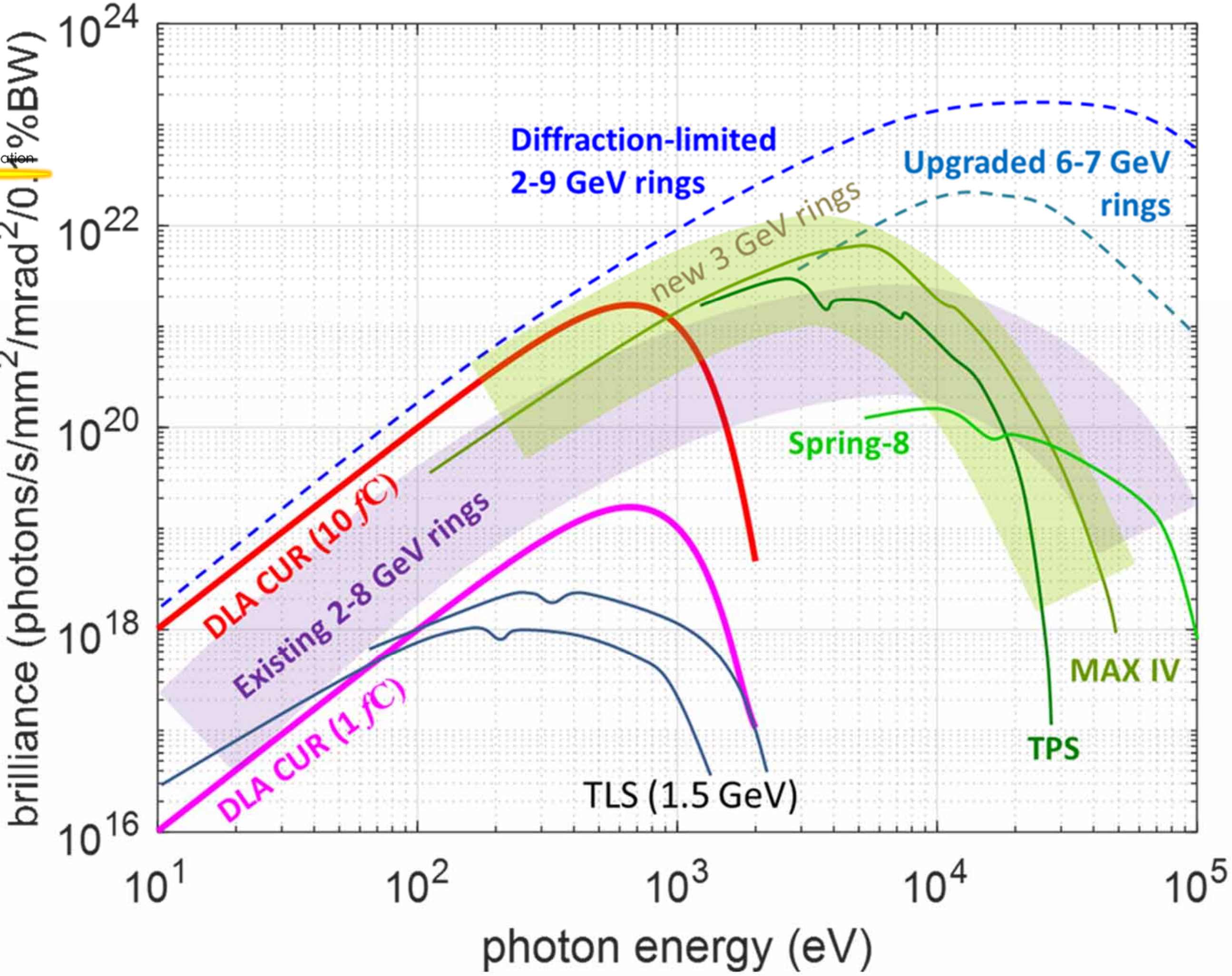


0.5 kW ~ 5 W power (adapted from https://achip.stanford.edu/)

Dielectric laser accelerator



System parameters		
item	unit	quantity
Driving laser wavelength, λ	μm	1
FWHM bunch length, τ_b	attosecond	2.35
Bunch Charge	fC	1, 10
Bunch rate, f_b	GHz	1
Beam energy	GeV	< 0.5
Undulator period	mm	1
Undulator parameter, a_u	NA	0.22
Number of undulator periods, N_u	NA	1000



*Curves other than DLA CUR are adapted from Zirong Huang, SLAC-PUB-15449.

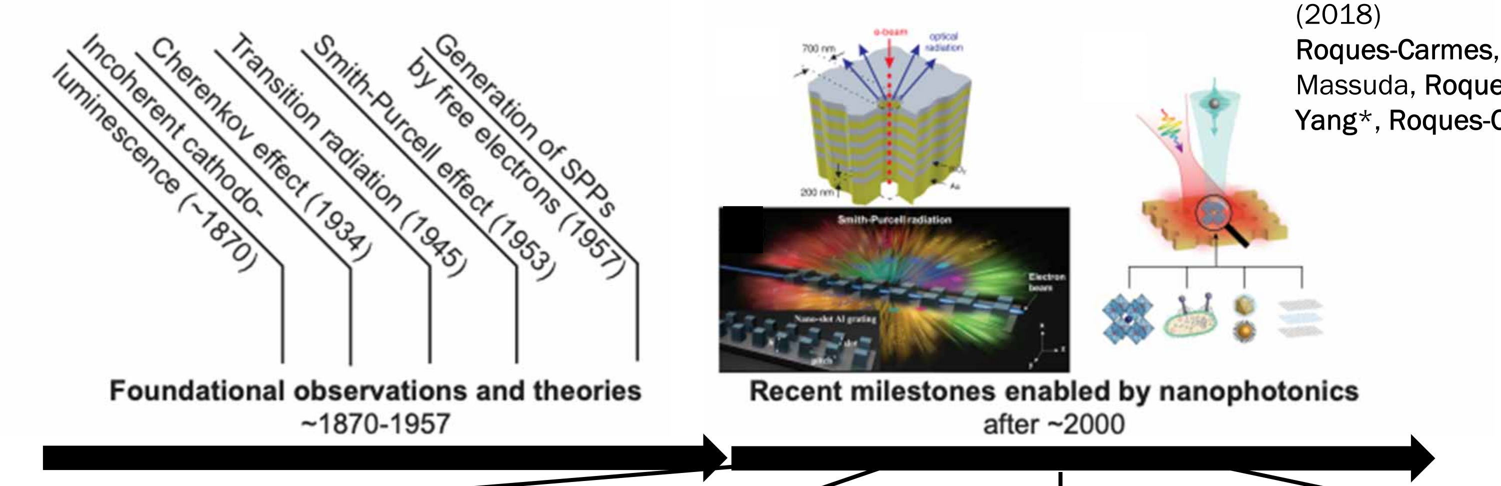
MO1L2

Free-electron-light interactions in nanophotonics

Charles Roques-Carmes, Stanford University, chrc@stanford.edu

- **Modelling**, **tailoring**, and **enhancing** coherent electron-light interactions with nanophotonic structures

See also:
Roques-Carmes et al., Applied Physics Reviews (2023)
Yang, Massuda, Roques-Carmes, et al., *Nature Physics* (2018)
Roques-Carmes, et al. *Nature Communications* (2019)
Massuda, Roques-Carmes, et al., *ACS Photonics* (2018)
Yang*, Roques-Carmes*, *Nature* (2023)



Nanofabrication for nanophotonics

Free-electron quantum optics (2020-)

Nanophotonic scintillators (2022-)

Single electron/x-ray cameras (Timepix, 2015-)

"I have presented a general framework to model, tailor, and enhance coherent electron-light interactions with nanophotonic structures. …
This also paves the way to some of the very exciting applications of the field of free-electron quantum optics."

WE2C2

Harmonic Generation from keV-electron-excited Nano-grating

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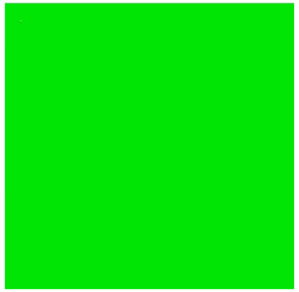
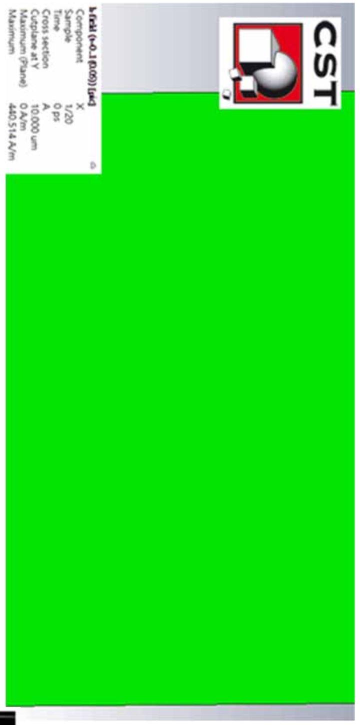
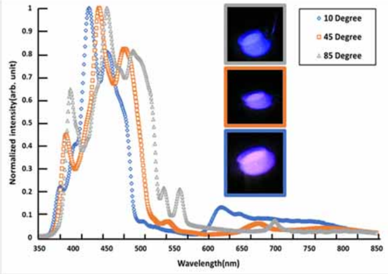
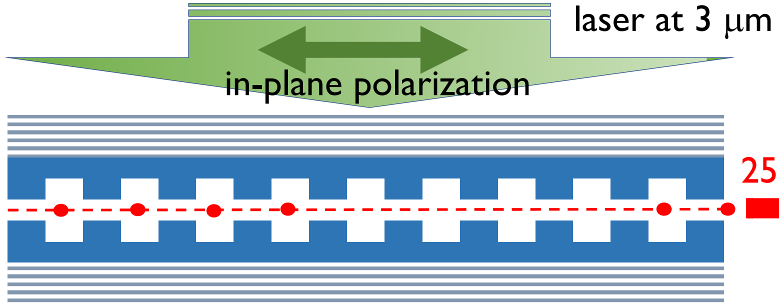


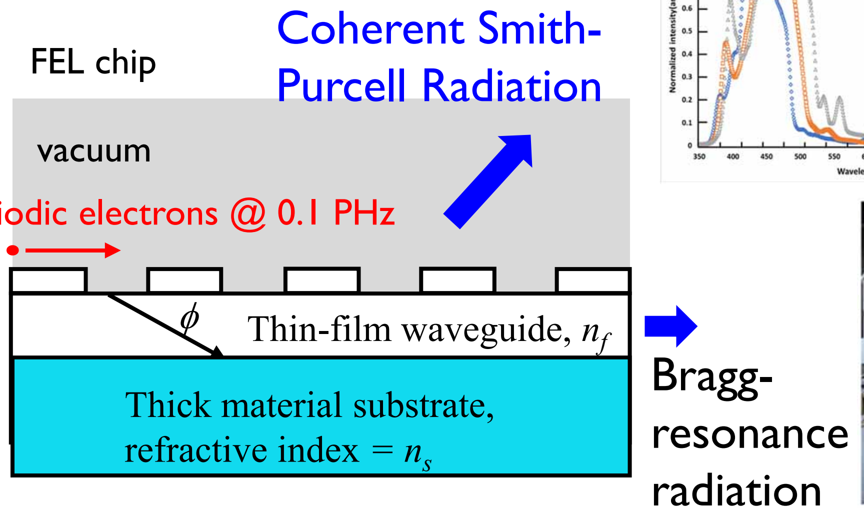


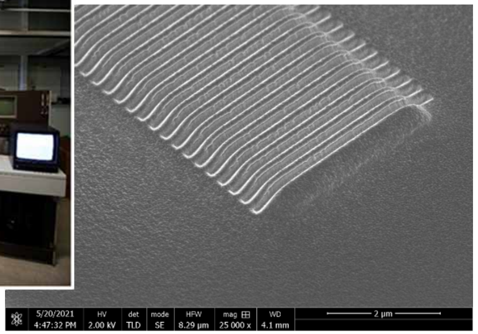
Dielectric laser accelerator and photonic FEL can be integrated into a chip-size substrate via microfabrication techniques.



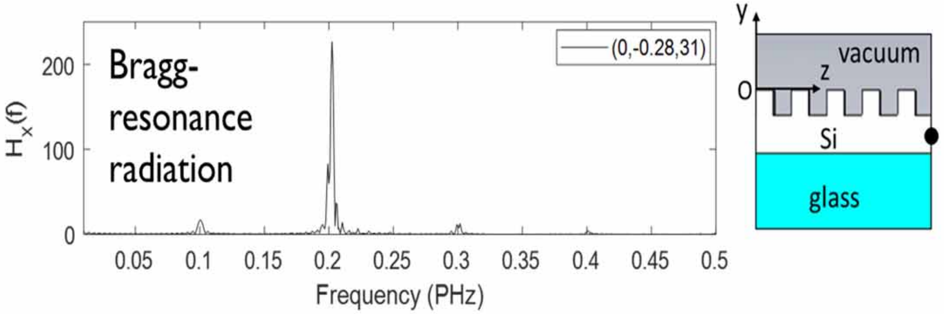


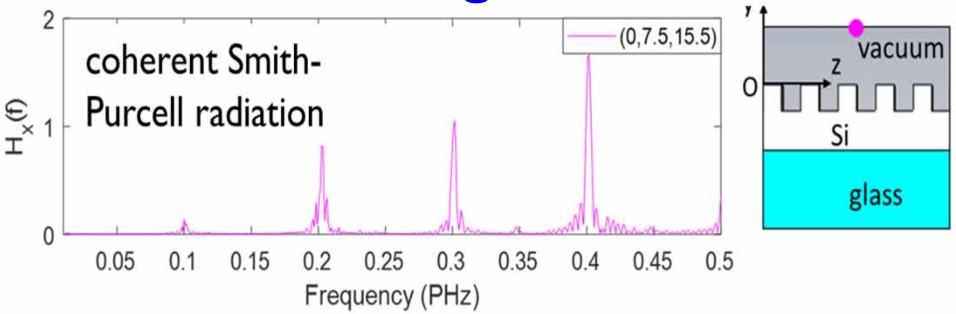
Dielectric laser accelerator driven by a 3 μm (0.1 PHz) laser

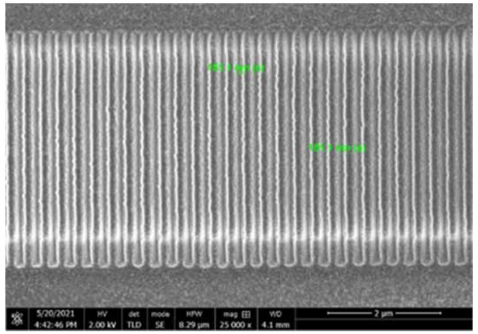




coherent harmonic radiation from a train of single electrons







Thanks to the WG-C Members and FLS’23 Workshop attendees

THANK YOU FOR YOUR ATTENTION