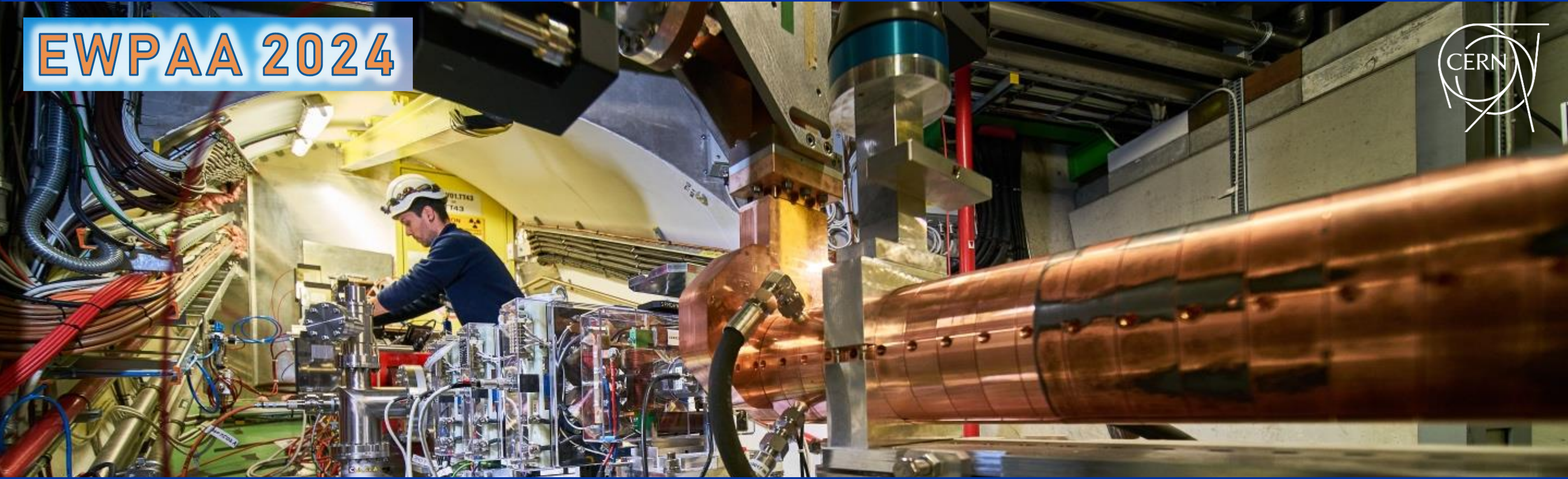


Boosting Photocathode Performance through Plasmonic Effects and In-situ Rejuvenation Techniques

***E. Granados**, M. M. Calderon, B. Groussin, P. Katona, L. Jones, E. Chevallay, R. E. Rossel*

… and many others

EWPAA 2024, 17th September 2024

Outline

Our team at CERN

- Introduction, key areas of expertise

Electron sources at CERN

- CLEAR electron source
  - Photoinjector
  - Photocathode rejuvenation
  - New Electro-optic 12 GHz rep rate photoinjector laser
- AWAKE electron source(s)
  - Overview
  - Photocathode production, transport in the

Photoemission laboratory

- Plasmonic photocathode research
- Interest in nanophotonics: electron production / manipulation, diagnostics / sensors, novel accelerators

Conclusions

Lasers and photocathodes team at CERN

"The Lasers & Photocathodes section is responsible for ***laser installations and optical beamlines used to produce charged particle beams*** in the CERN accelerators complex and research facilities"




Current members:

Katerina Chrysalidis – STAFF
Eduardo Granados – STAFF
Ralf Rossel – STAFF

Isabelle Fontaine – TEMC
Anahita Omoumi– FELL
Cyril Bernerd – FELL
A. Ajayakumar – GRAP
J. Reilly – GRAP

Ralitsa Mancheva – DOCT
Eva Roikova – DOCT
J. Wessolek – DOCT
A. Jaradat – DOCT
Palma Katona – TECH
M. Fenech – TNRE
A. Aggarwal – TECH

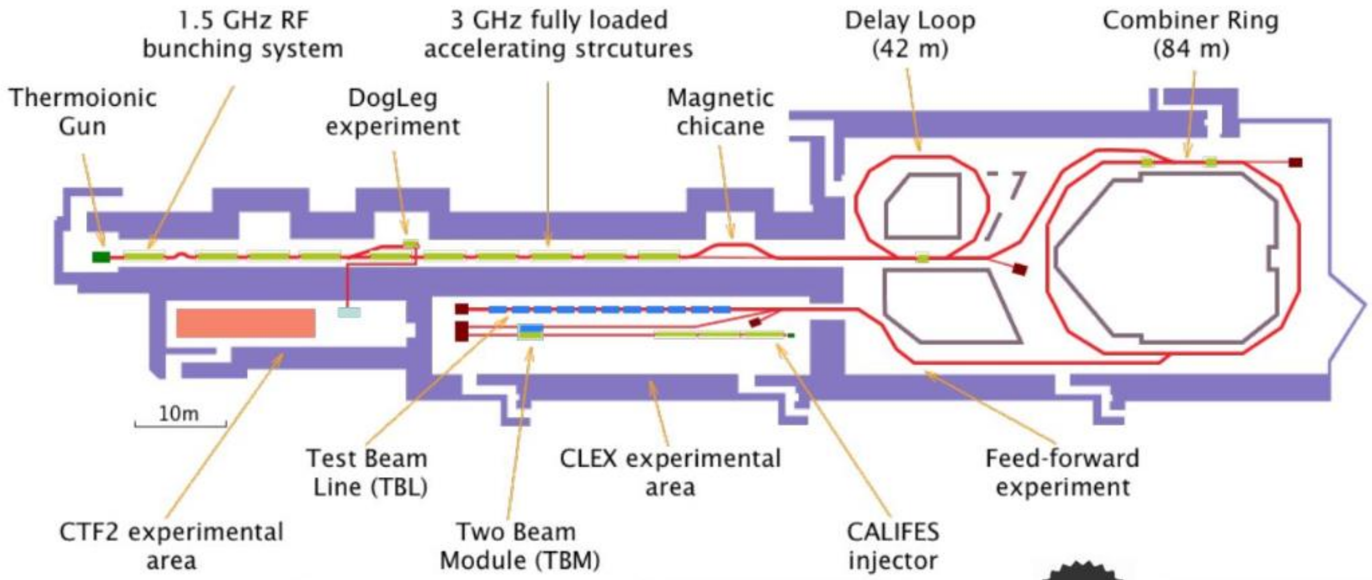
Former members:

Bruce Marsh
Valentin Fedosseev
Eric Chevallay
Shane Wilkins
Camilo Granados
Matthieu Veinhard
Christoph Seifert
Tom Day Goodcare
Sebastian Rothe
Daniel Fink
Harsha Panuganti
Anna-Maria Bachmann
Florence Friebel
Daniel Talan Echarri
Reinhard Heinke
Christoph Hessler
Mikhail Martyanov
Piotr Gach
Irene Martini
Marta Csatari Divall
Massimo Petrarca
Nathalie Lebas
Vaila Leask
Vadim Gadelshin
Miguel Martinez-Calderon
Baptiste Groussin

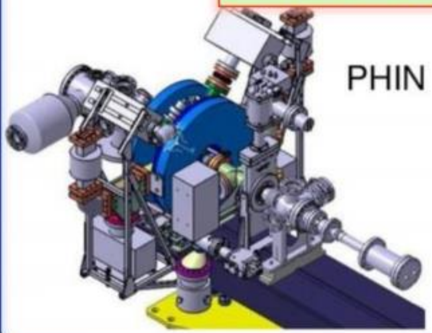




CLIC Test Facility heritage



DRIVE beam



PHIN

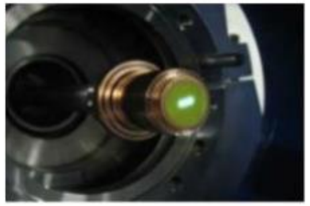
Cs_2Te / Cs_3Sb
Co-deposition

Now at:

AWAKE

MAIN beam

Cs_2Te @ CALIFES
In-situ, dual layer

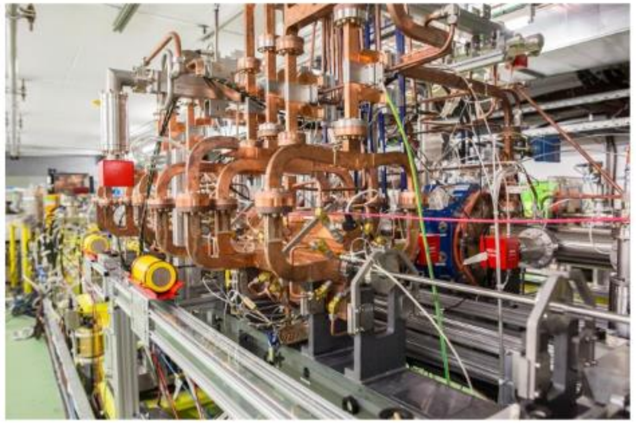


NEW

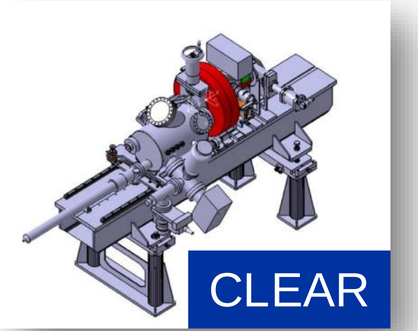
clear

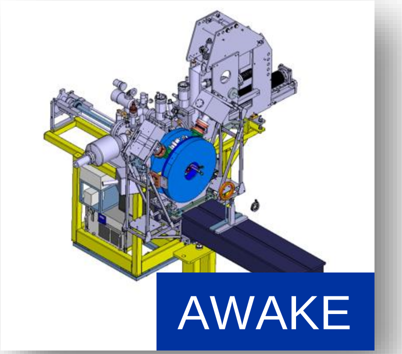
Test facility for:

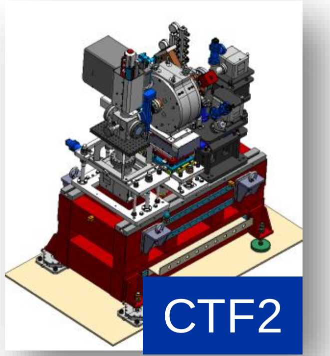
- X-band technology
- Bunch compression
- Advanced beam dynamics
- Plasma lens, AWAKE…
- Wakefield physics
- Radiation studies

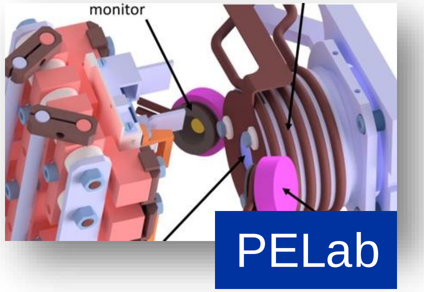


Currently operative electron sources at CERN





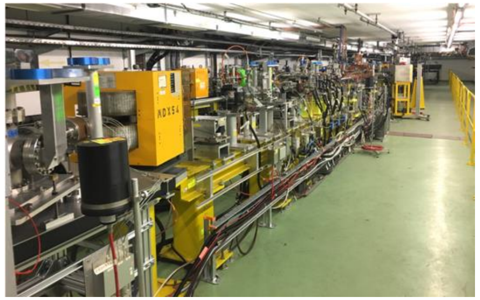


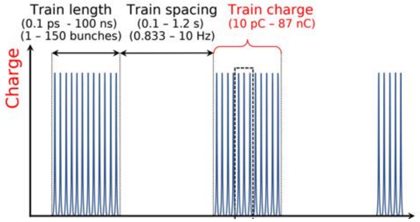


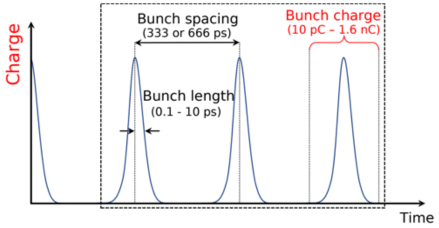
	CLEAR	AWAKE	CTF2	PELab	
Photocathode technology	Cs_2Te In-situ	Cs_2Te / Cs_3Sb Load-lock	Cu	Cs_2Te Cs_3Sb KCsSb	Cu Mo Plasmonic
Quantum efficiency	1-5%	5-20%	0.01%	1-20%	0.01-0.2%
Charge production	7 nC/bunch 150 bunches	1 nC Single bunch	400 pC **Single bunch**	10s nC Single bunch	
Laser driver	Nd:YLF 1 uJ, 4.8 ps	Ti:Sapphire 0.2 uJ, 1.2 ps	Yb:KGW (Pharos) **400 uJ**, 200 fs	Nd:YAG 7 mJ, **8 ns**	
Use	User beamtimes CLEAR	Witness, SM AWAKE run 1-2b	Witness, AWAKE run 2c	AWAKE production	

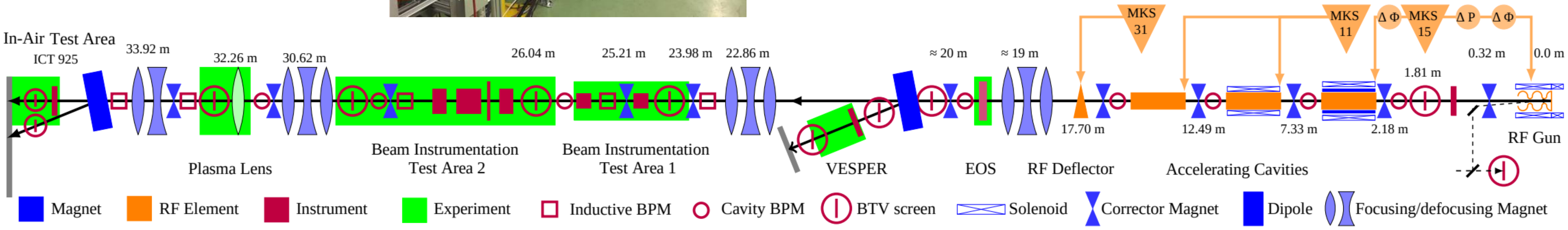
CLEAR user facility electron beamlines

2017-2030





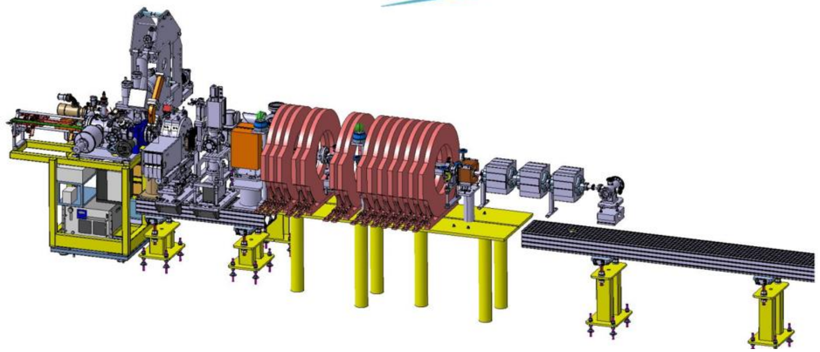


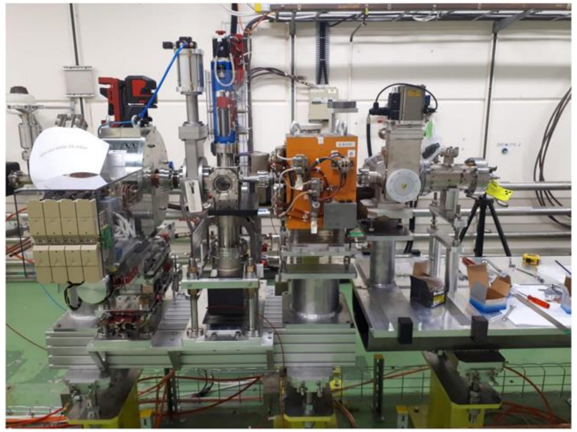


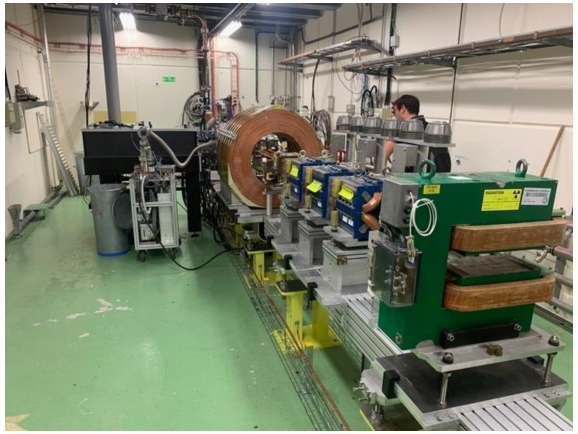
CLEAR
30 - 220 MeV
7 nC/bunch
1 - 150 bunches
1 - 10 Hz
1.5 – 3 GHz

CTF-2

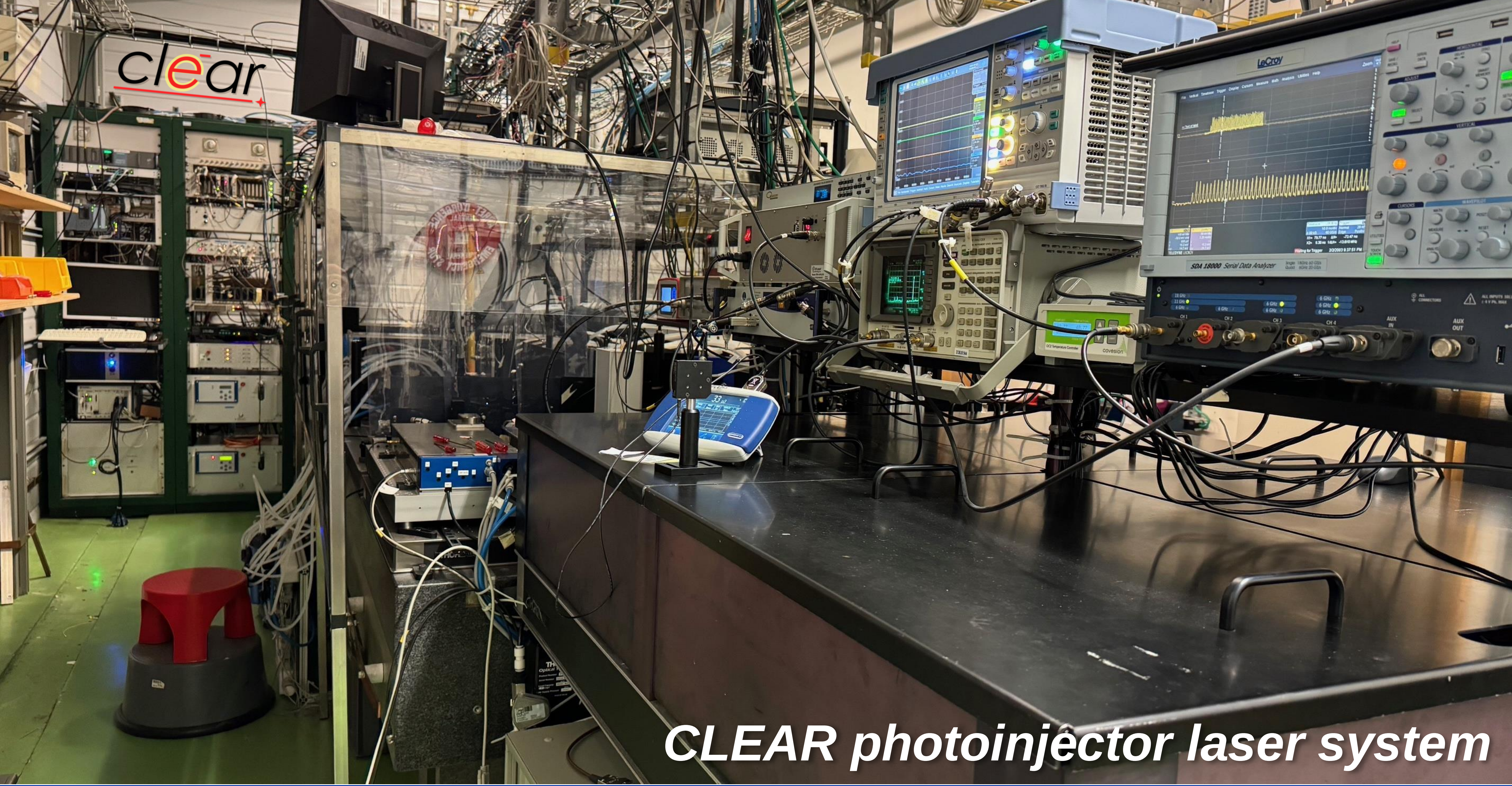
2023-?







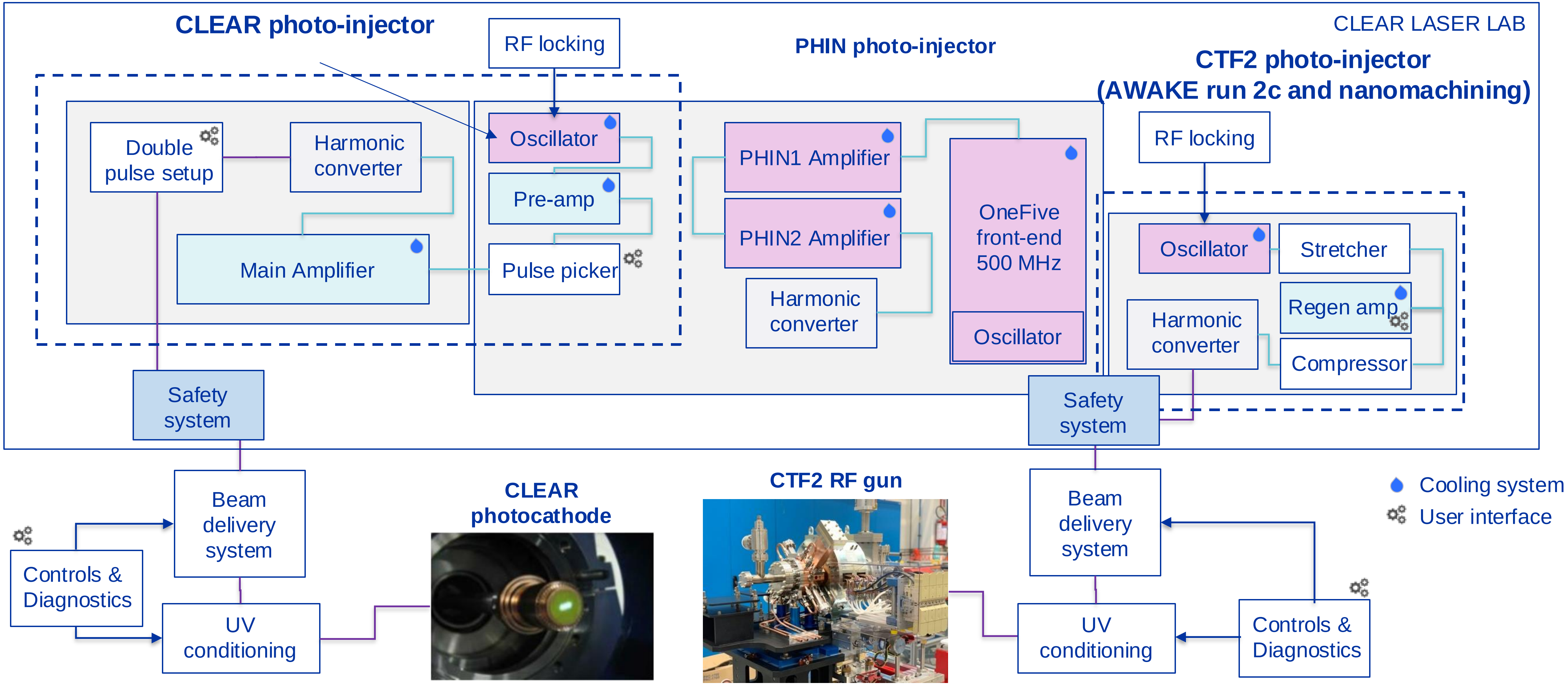
CTF2 / CLIC
6 - 150 MeV
1 nC/bunch
1 bunch
1 - 10 Hz
Under development



CLEAR photoinjector laser system

“oldie but goodie”

Laser systems at CLEAR



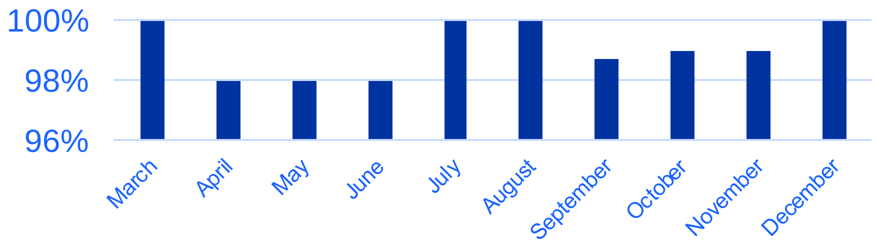
Example: operation during 2023

	March	April	May	June	July	August	September	October	November	December
	JUAS	LUXE beam profiler detector (INFN Bologna)	CHUV – FLASH	Cherenkov BPMs (INFN Bologna)	LHC dielectric Cherenkov detectors	Plasma lens (University of Oslo)	VHEE scatterers dosimetry	Emittance measurements (Liverpool)	Broadband pickups (PSI)	Real-time VHEE dosimetry
	Neutron monitors (Politecnico di Milano, PSI, ELI)	Passive dosimetry	FCC Bunch length monitor	EO sampling	FCC-ee Bunch profile monitor (KIT)	VHEE scatterers dosimetry (Oxford)	AWAKE Cherenkov BPMs (Oxford)	HL-LHC cable ageing research (CARE)	Radiation hardness (IRRAD)	AWAKE spectrometer
Beamtimes	Real-time dosimetry (Oxford)	Beam scatterers (Oxford)	VHEE UHDR (University of Victoria)	Quartz fiber detectors	Real time beam dose monitors (Oxford)		CHUV Chemistry	VHEE passive dosimetry	CHUV - FLASH	
	Beam scatterers	Bergoz wall current monitor	Cherenkov BPMs (Oxford)	CLEAR MD			Real-time dosimetry (Strathclyde)	FCC Cherenkov BPMs + BLM	Real-time VHEE dosimetry	
	LUXE beam profiler detector (INFN Bologna)	Plasmid irradiations (Manchester)	CLEAR MD				Beam loss monitors in silica fibers (Liverpool)	Broadband pickups (PSI)	3D Si, diamond sensors (University of Kansas)	
		CHUV FLASH					Cavity BPMs (Royal Holloway)			
Photoinjector Issues	No issues	6 h down due to laser chiller	Laser amplifier failure 6 hours	Laser synchronization downtime ~6 h	No issues. Laser maintenance performed	Laser oscillator refurbished during summer downtime	Laser amplifier failure 2h. Power cut 2h	Temperature fluctuations, 2h downtime	Laser synchronization issues: 3h downtime	Amplifier power supply failed, although **80h+/week**!
uptime	100%	98%	98%	98%	100%	100%	98.7%	99%	99%	100%

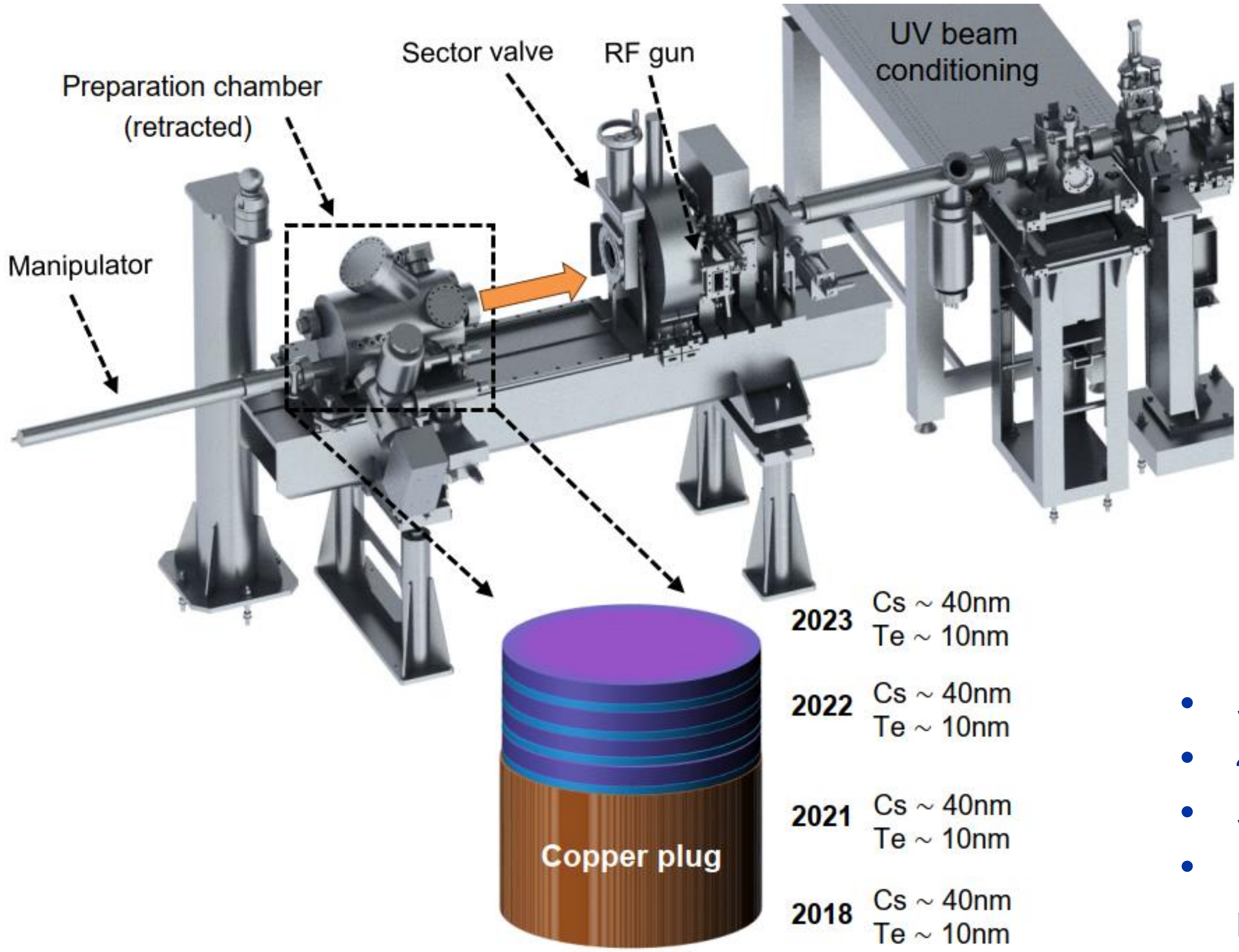
35 beam-times in 2023 (mostly external users), typically 70 h/week

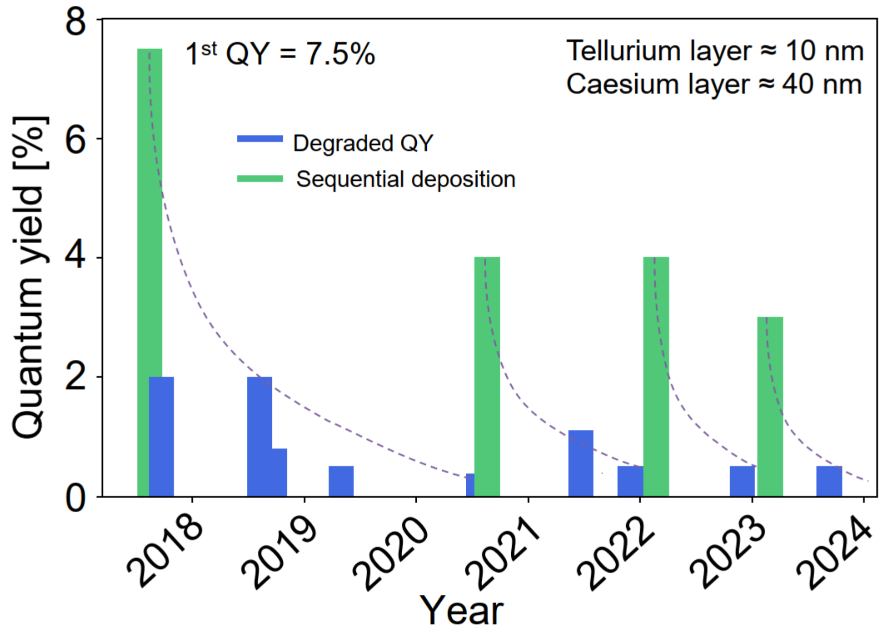
Laser up-time total ~6500 h, down-time ~27 h (up 99.6%). Laser available 24/7 usually

New front-end laser based on programmable Electro-Optic (EO) comb currently under construction



CLEAR photocathode rejuvenation

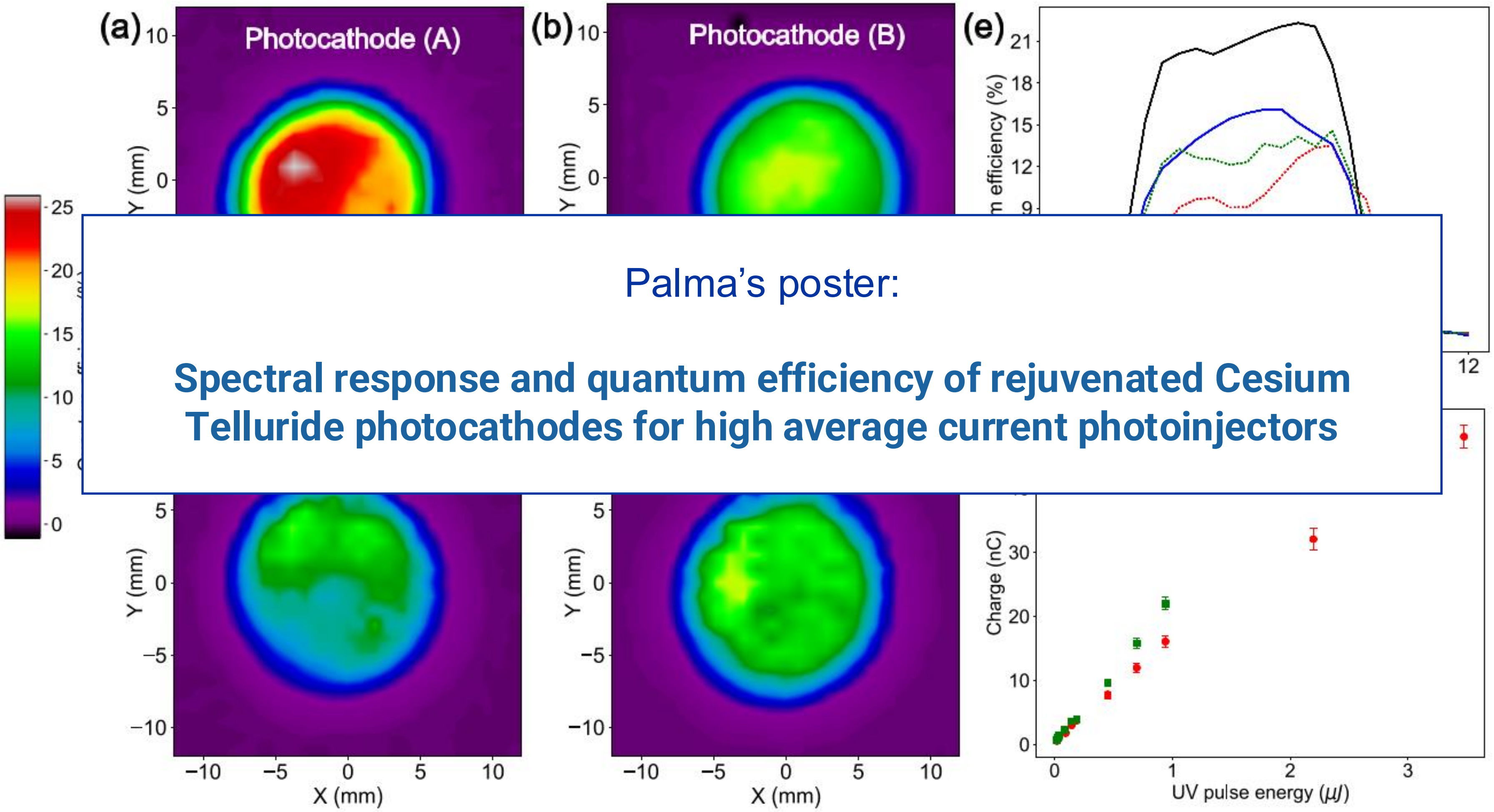




- Sequential deposition is suboptimal.
- 4 rejuvenations carried out successfully.
- Slight decrease of achievable QE.
- Extracted more than 1 Coulomb between rejuvenations.

M. Martinez-Calderon, E. Chevallay, R. E. Rossel, L. B. Jones, G. Zevi Della Porta, B. Marsh, and E. Granados
Phys. Rev. Accel. Beams 27, 023401 (2024)

Homogeneity of rejuvenated cathodes

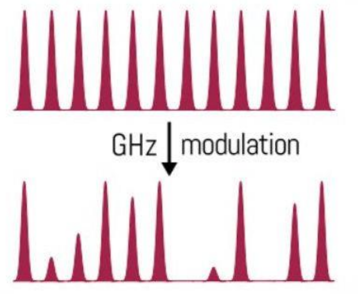


Palma’s poster:

Spectral response and quantum efficiency of rejuvenated Cesium Telluride photocathodes for high average current photoinjectors

M. Martinez-Calderon, E. Chevallay, R. E. Rossel, L. B. Jones, G. Zevi Della Porta, B. Marsh, and E. Granados
Phys. Rev. Accel. Beams 27, 023401 (2024)

New CLEAR photoinjector laser

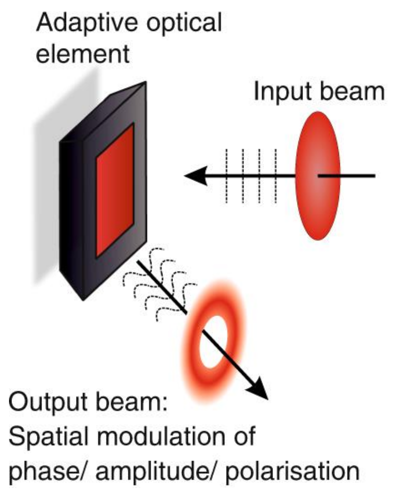


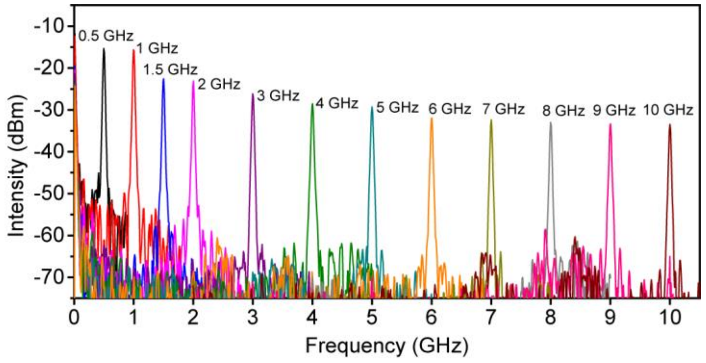
Operating at arbitrary rep. rate MHz up to 12 GHz, programmable pulse duration

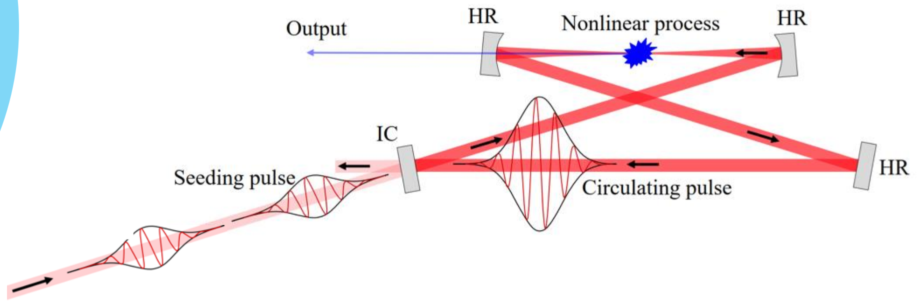
Programmable trains with arbitrary amplitude and beam profile, FCC-ee "top up scheme"

?

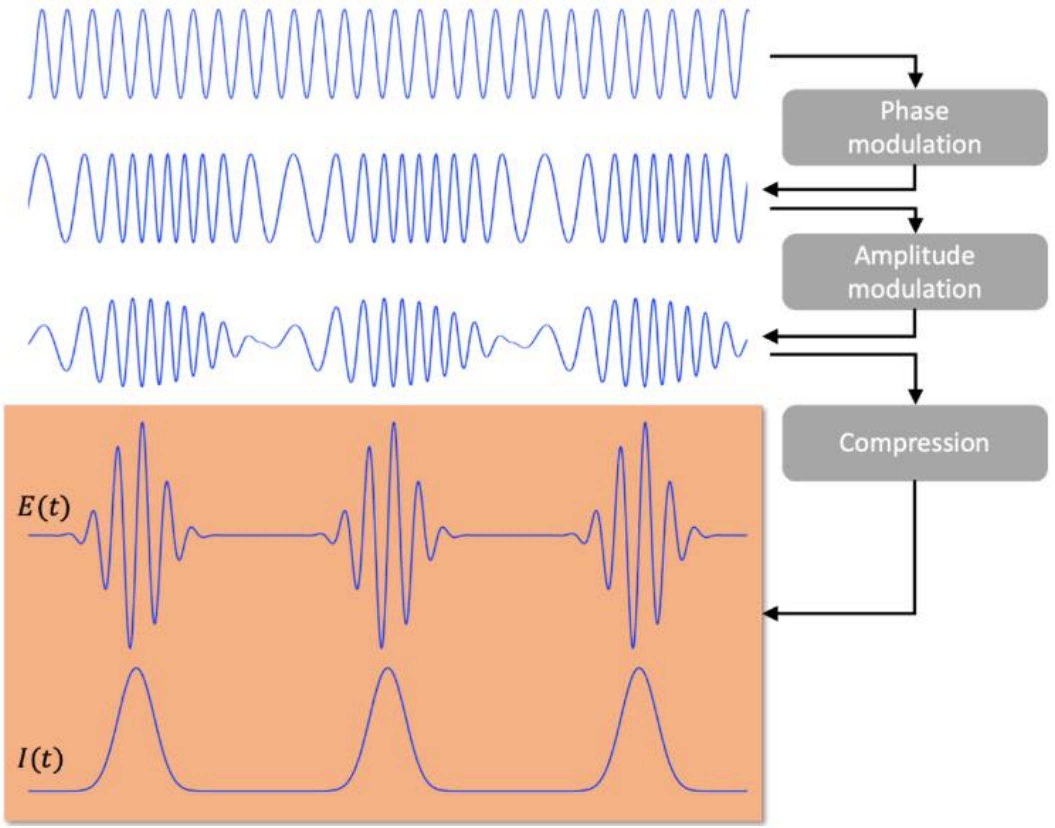
Phase-stability enabling ultra-high intensity laser-electron interaction

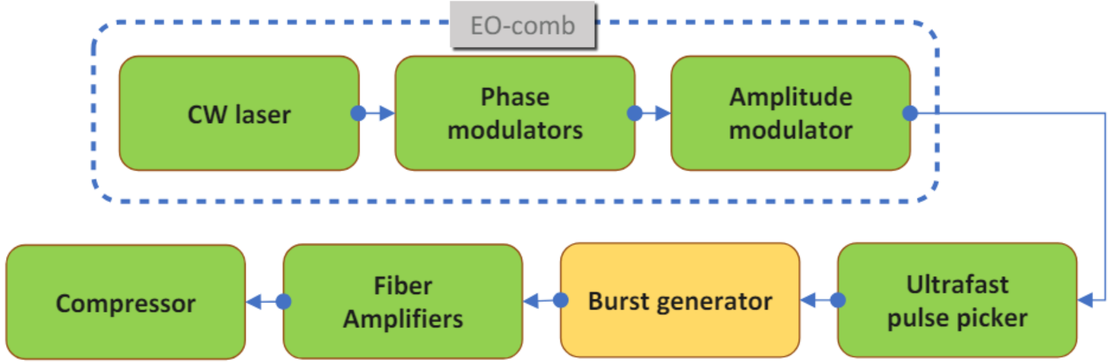


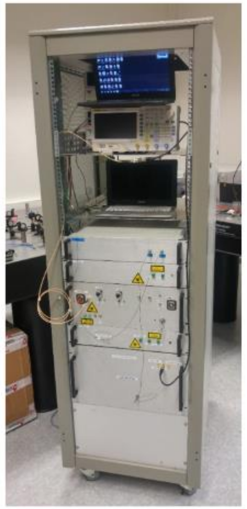




Electro-optic frequency comb laser system



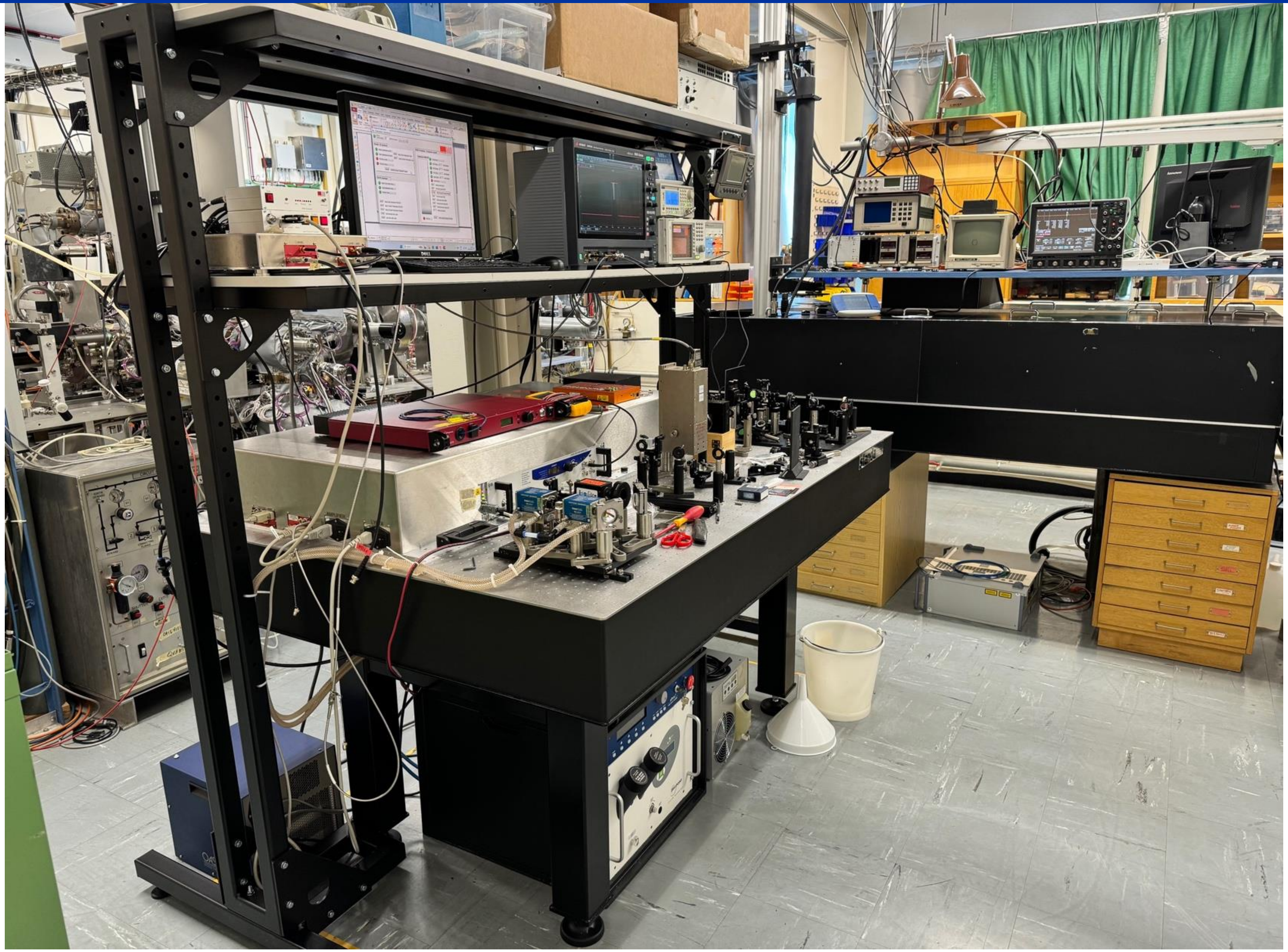




Gigapico Burst Mode:

Wavelength (Yb):	1030 nm
Average power:	40 W
Maximum burst energy:	1 mJ
Maximum pulse energy:	10 µJ
Pulse repetition rate :	0.25 GHz to 18 GHz
Burst repetition rate:	50 kHz to several MHz
Pulse duration:	800 fs to 2 ps
Number of pulses per burst:	10 to several 1000

Electro-optic frequency comb development status



Prototype under construction in Photoemission lab

90% of required items already procured

Many recycled items from CLIC:

- CLIC burst amplifier,
- CLEAR booster amplifier,
- CLIC harmonic conversion stages,
- Amplitude modulators and fiber systems for phase-coding project.
- Optical elements
- Pulse picker from PHIN

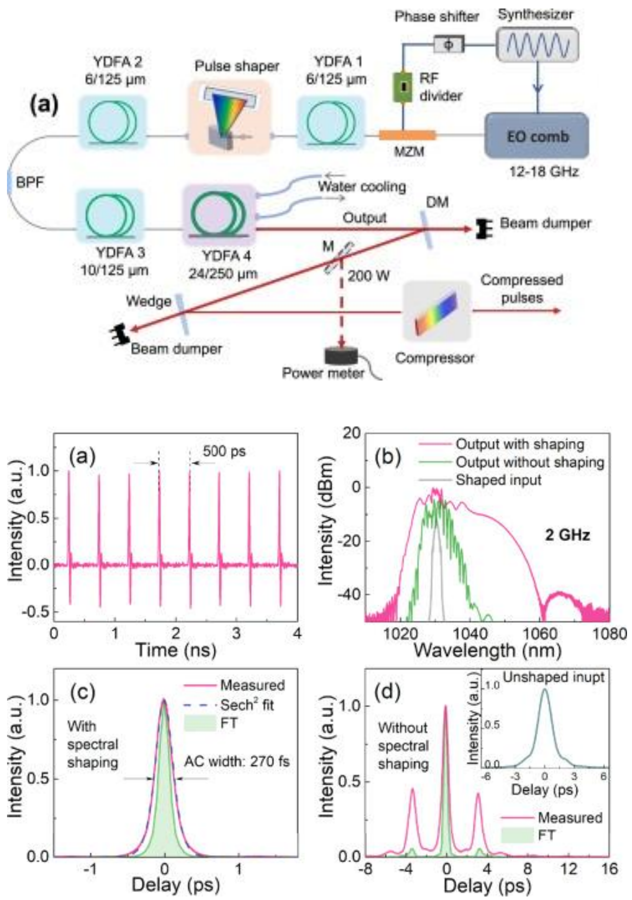
Synergy with developments for Gamma Factory PoP experiment at SPS and Compton polarimeter for FCC-ee.

Fully programmable system: Can also simulate FCC-ee electron bunch structure.

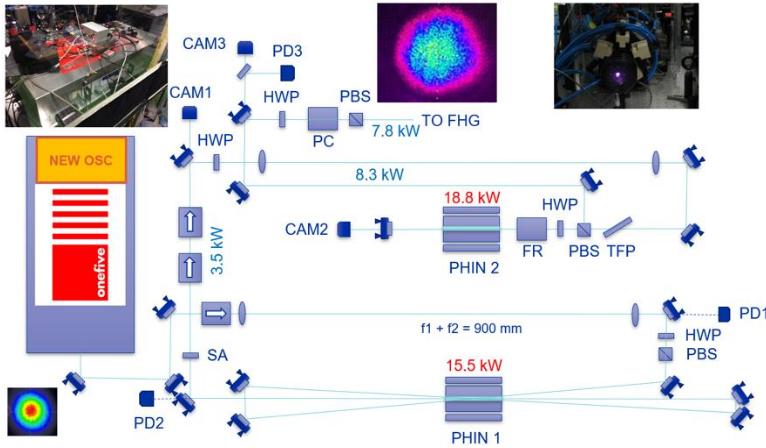
ICS X-ray sources program at CERN

1-12 GHz rep rate Electro-Optic frequency combs

Opt. Express 30, 10605-10613 (2022)

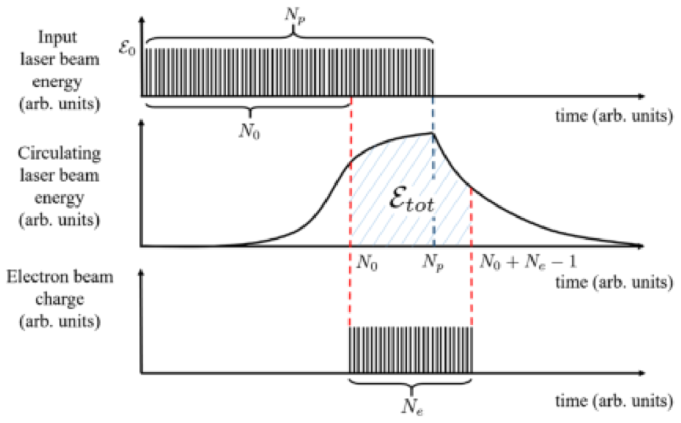


Burst Amplification Chain to >1J/train

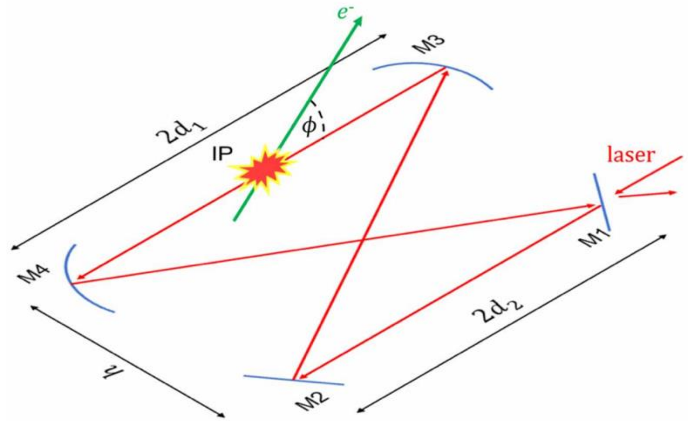


Material / Wavelength	**Nd:YLF / 1047 nm**
Pulse duration / Rep Rate	4 ps / 1.5 GHz
Pump power (burst)	20 kW
Train duration	250 us
# pulses/train	375,000
Train rep rate	5 Hz
Average Power	10 W
Energy/pulse	5 uJ / pulse
Energy/train	**2 J / train**

Burst-mode Fabry-Perot enhancement cavity

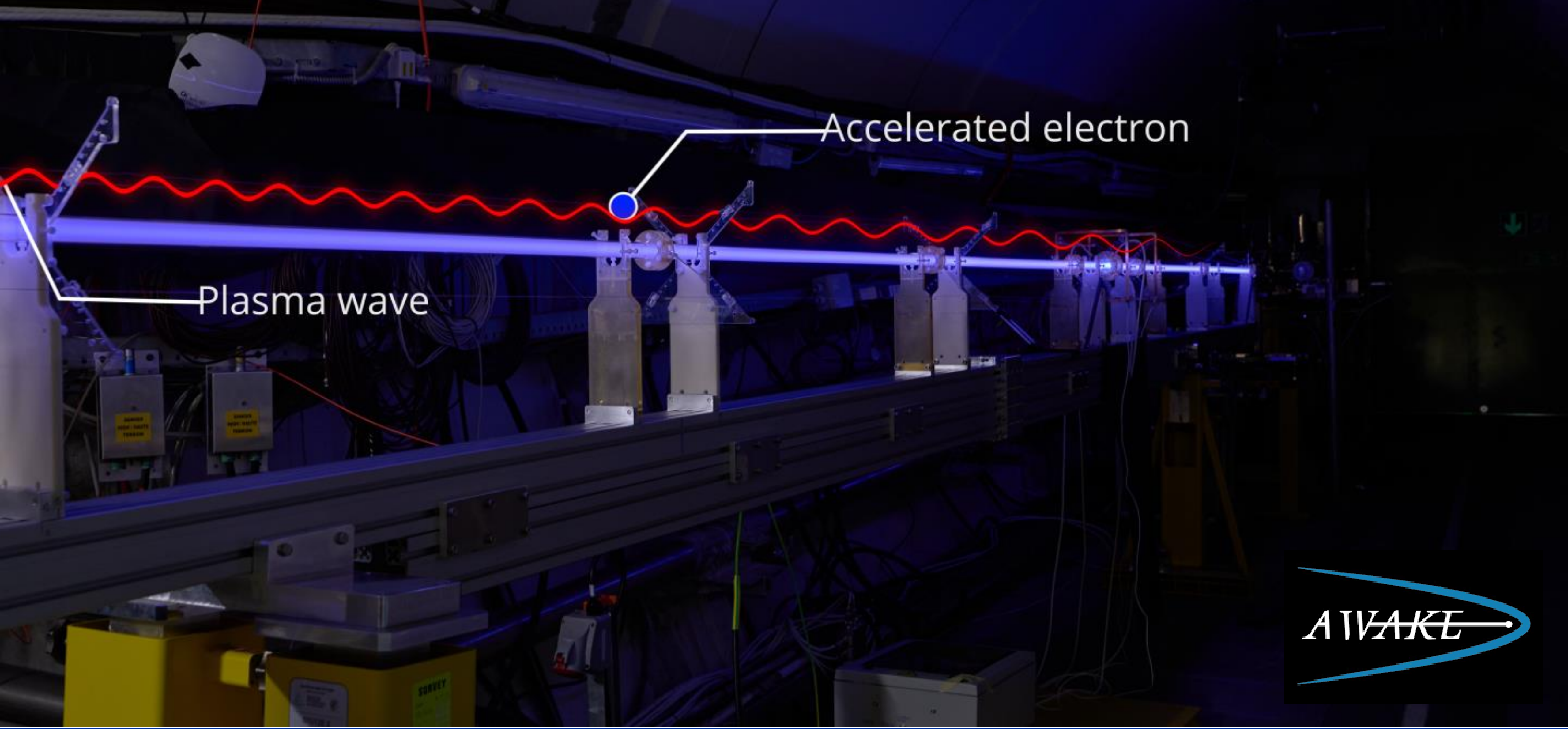


Phys. Rev. Accel. Beams **21**, 121601 (2018)



“An Efficient Optimisation of a Burst Mode-Operated Fabry-Perot Cavity for Compton Light Sources”, doi:10.18429/JACoW-FLS2023-TU1C1 (2023)

Advanced Wakefield Accelerator Experiment (AWAKE)



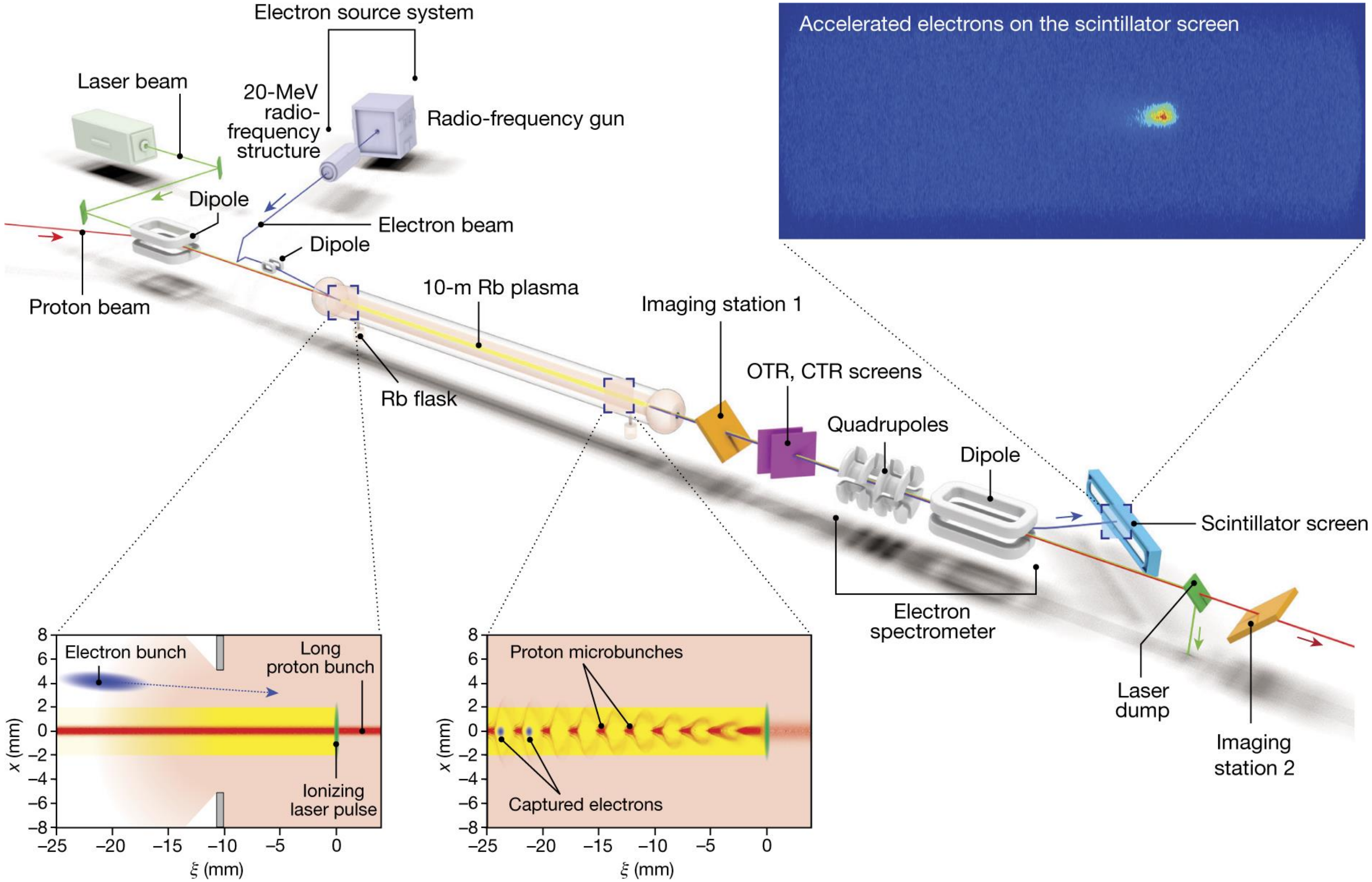
Advanced Wakefield Accelerator Experiment (AWAKE)

Proof-of-principle experiment: wakefield plasma acceleration using a proton bunch as a driver, a world-wide first.

It demonstrated acceleration of a low-energy witness bunch of electrons from 15-20 MeV to several GeV over a short distance (~10 m) by creating a high acceleration gradient of several GV/m

Our contribution:

- UV beam generation, delivery, and photocathode, diagnostics.
- IR beam delivery for plasma generation, diagnostics.
- Experimental and laser support

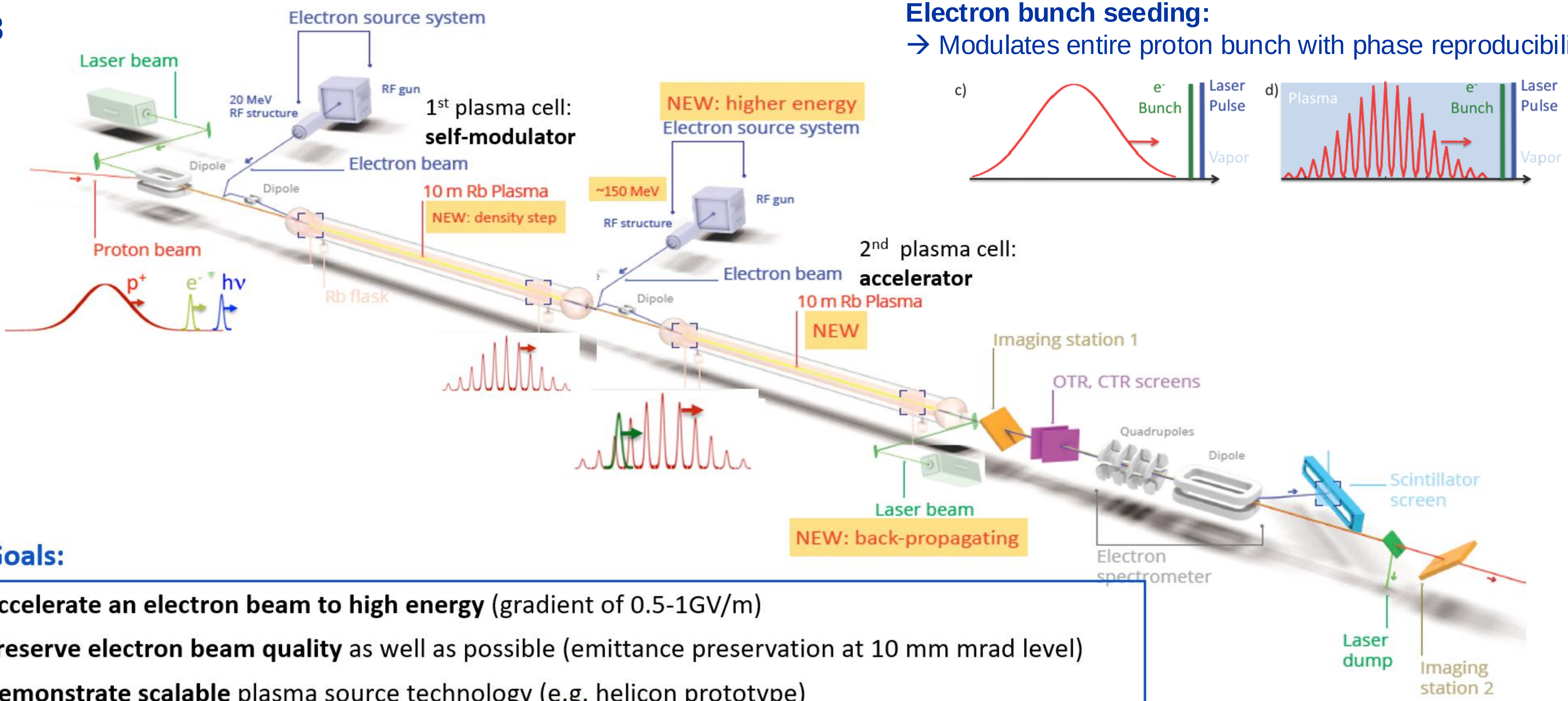


Nature volume 561, pages363–367 (2018)

Advanced Wakefield Accelerator Experiment (AWAKE)

2028

Electron bunch seeding:
→ Modulates entire proton bunch with phase reproducibility



Goals:

Accelerate an electron beam to high energy (gradient of 0.5-1GV/m)

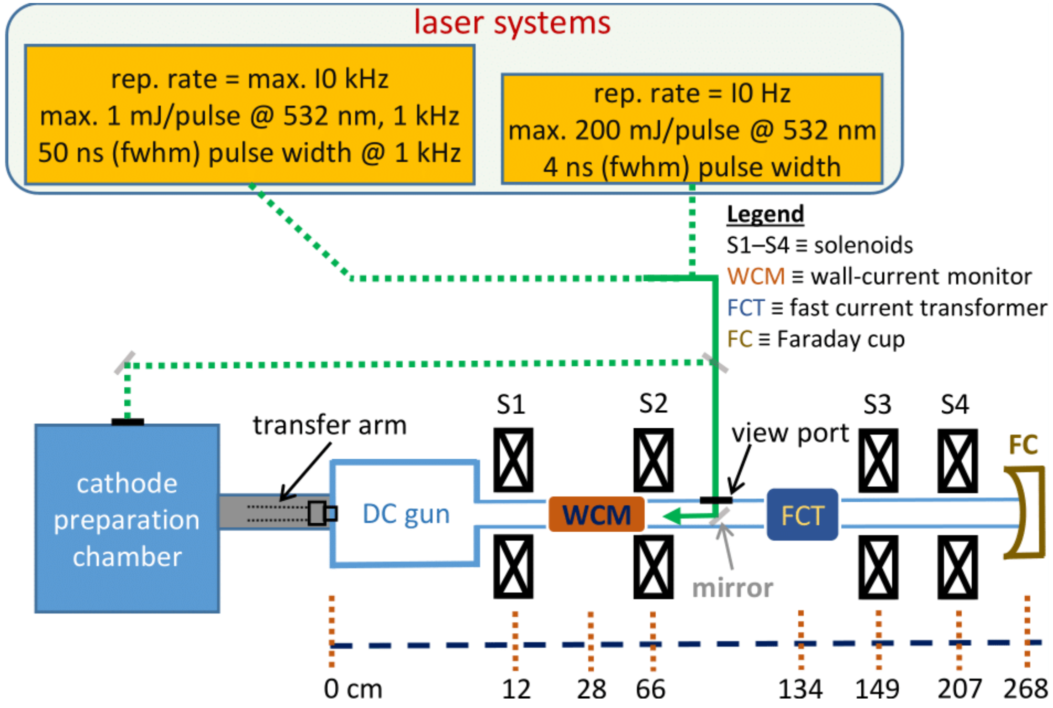
Preserve electron beam quality as well as possible (emittance preservation at 10 mm mrad level)

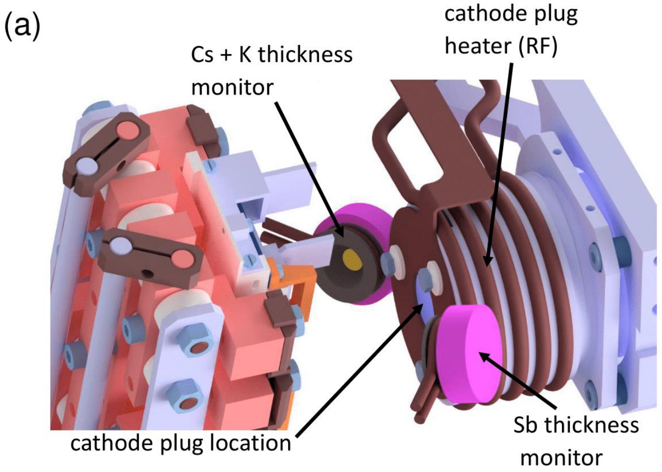
Demonstrate scalable plasma source technology (e.g. helicon prototype)

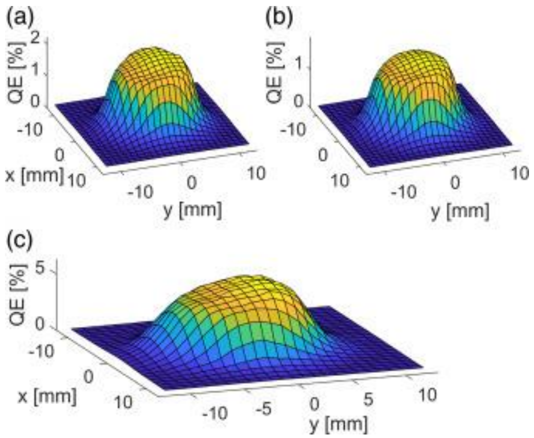
AWAKE photocathode production - Photoemission lab

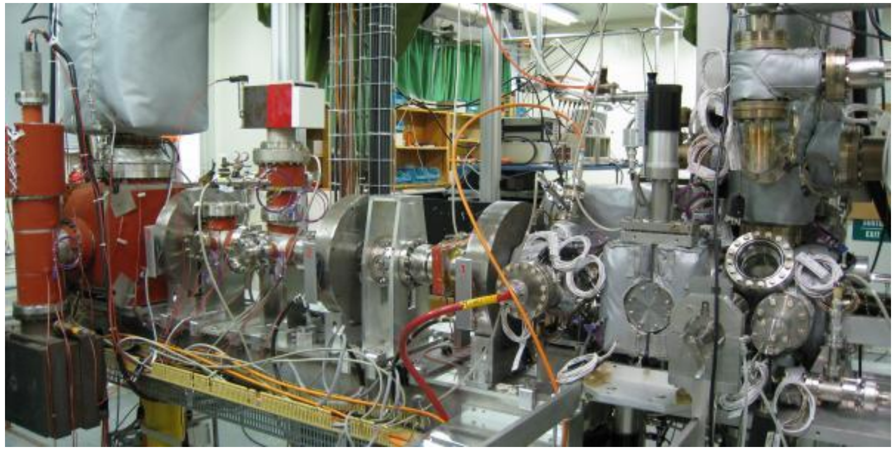
>25 years producing cathodes

Fabrication, lifetime studies, characterization









Past experiences

Class	Material	QE	Wavelength	Gun	Application
Normally conducting metals	Cu, Mg	10^{-5} - 10^{-4}	UV	NC-RF	Low Rep rate FELs (LCLS, SwissFEL…)
Super-conducting metals	Nb, Pb	10^{-5} - 10^{-4}	UV	SC-RF	High Rep rate FELs
Positive electron affinity semiconductor	Cs_2Te, Cs_3Sb , K_2CsSb …and others…	0.1 – 0.2	Visible – UV	NC-RF, DC	FELs, ERLs
Negative electron affinity semiconductor	GaAs, etc	0.1-0.35	IR – Visible	DC (XHV)	Polarized sources, ERLs (ALICE)

- **Metals**
  - Low quantum efficiency -> requires high power lasers -> plasma is formed
  - Robust and simple
- **Semiconductors**
  - High quantum efficiency at extended wavelength range.
  - More difficult to maintain – x-rays and ions can cause decomposition and surface damage, vacuum…
  - Cs_2Te is quite standard, but requires UV

- **CERN Photoemission lab**
  - Cs_2Te photocathodes (UV, high QE) → current workhorse for AWAKE and CLEAR guns.
  - Bi-alkali photocathodes (green, high charge) → proposed for CLIC.
  - Cu cathodes for single bunch RF guns
  - NEW: Plasmonically enhanced metal photocathodes.

Co-deposition process

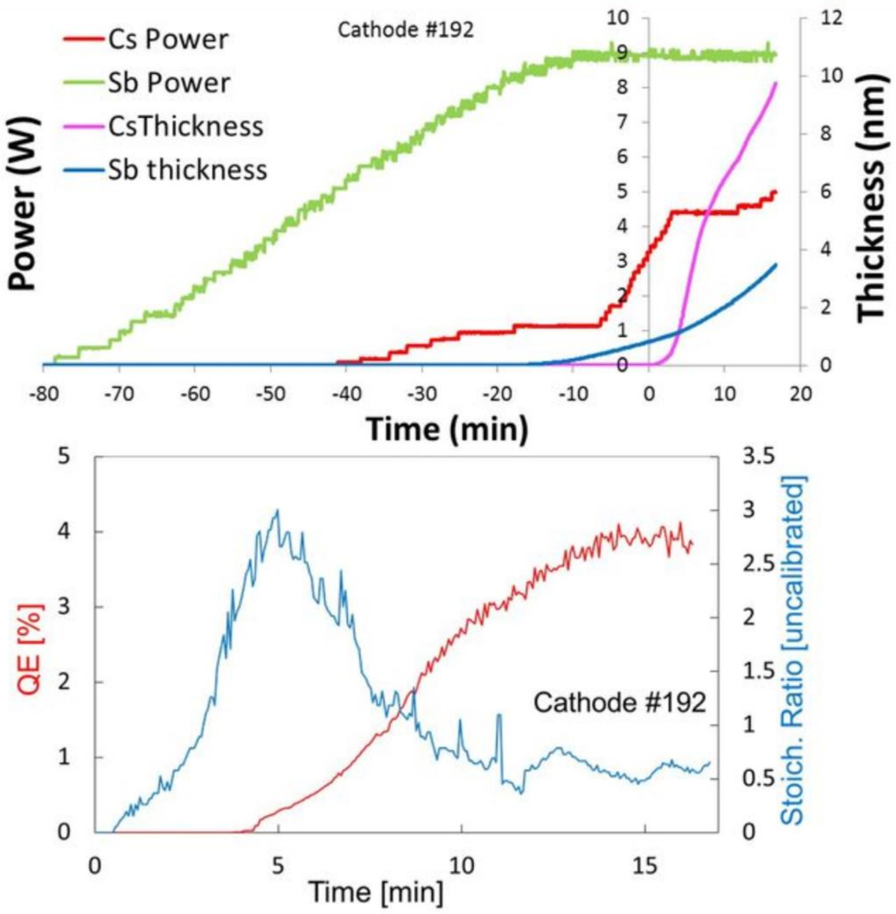
- ➢ **Co-deposition: Cs and Sb (or Te) evaporated at the same time. The metallic elements can mix together in the vapour phase.**

- ➢ **The evaporators power is adjusted in order to reach a maximum value of QE.**

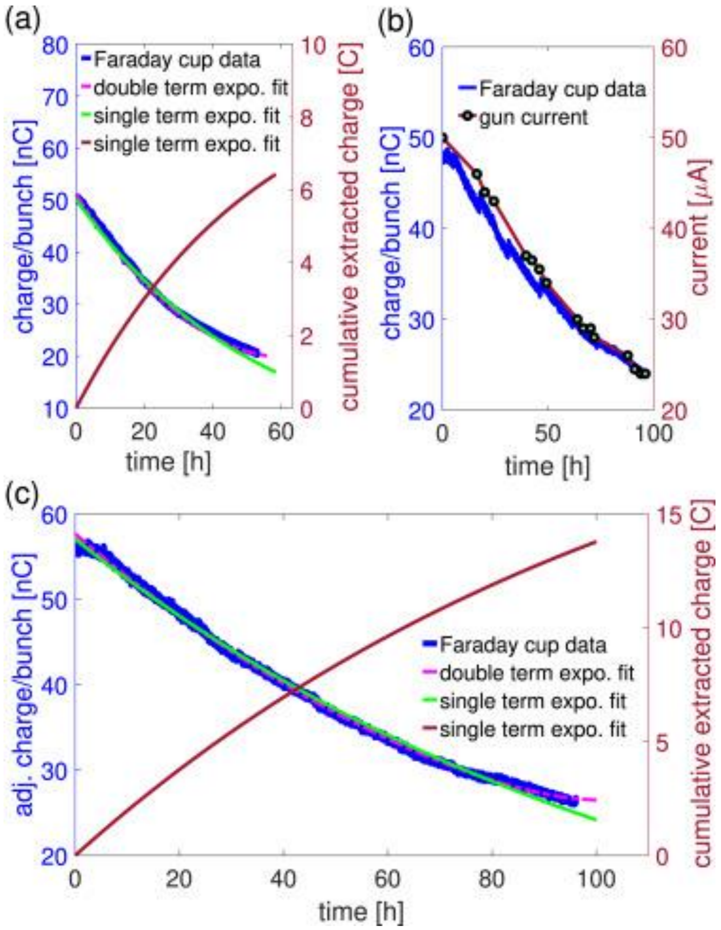
- ➢ **Average pressure during the process is 1e-8 mbar.**

- ➢**Once the cathodes are fabricated, they undergo QE testing spatially, lifetime studies and XPS characterization.**

Production process



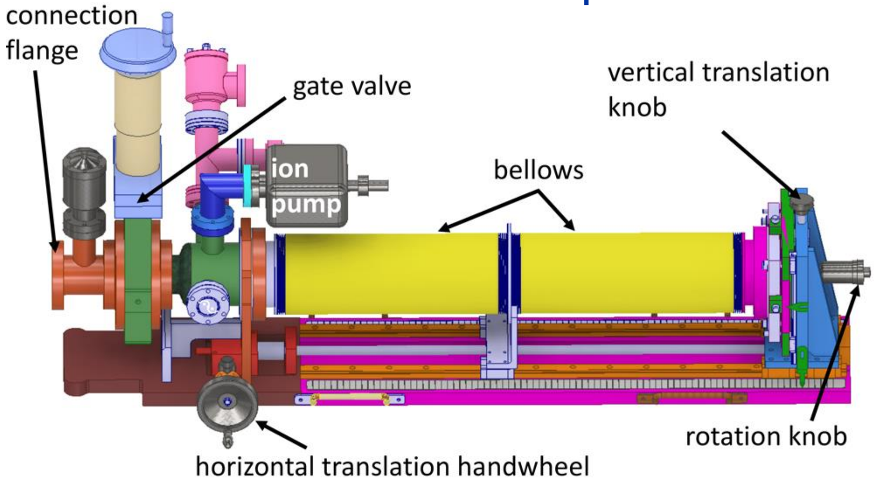
Lifetime studies

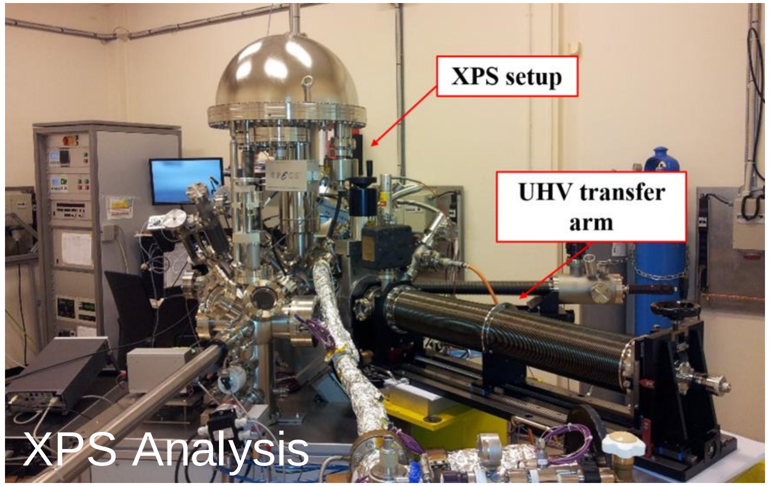


H. Panuganti, E. Chevallay, V. Fedosseev, M. Himmerlich, Synthesis, surface chemical analysis, lifetime studies and degradation mechanisms of Cs-K-Sb photocathodes, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 986, 2021

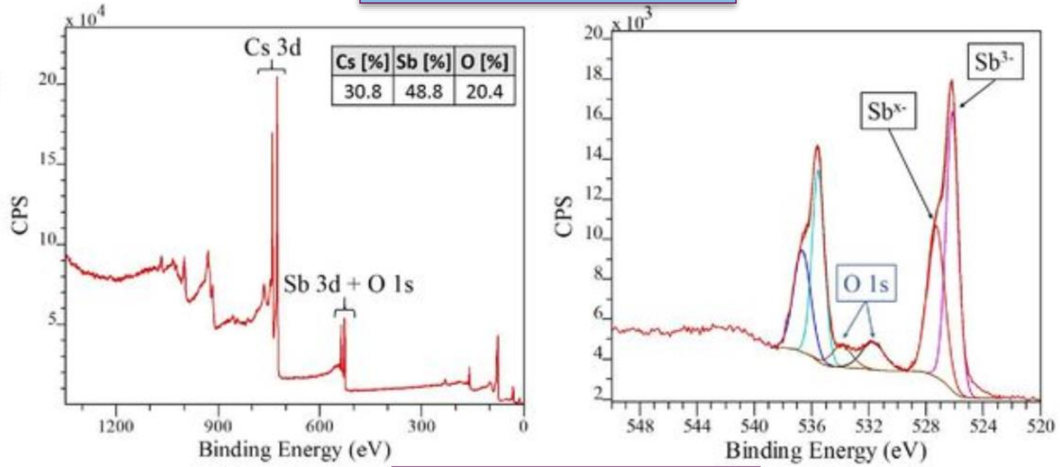
Photocathode transport and characterization (XPS)

Photocathode transport device

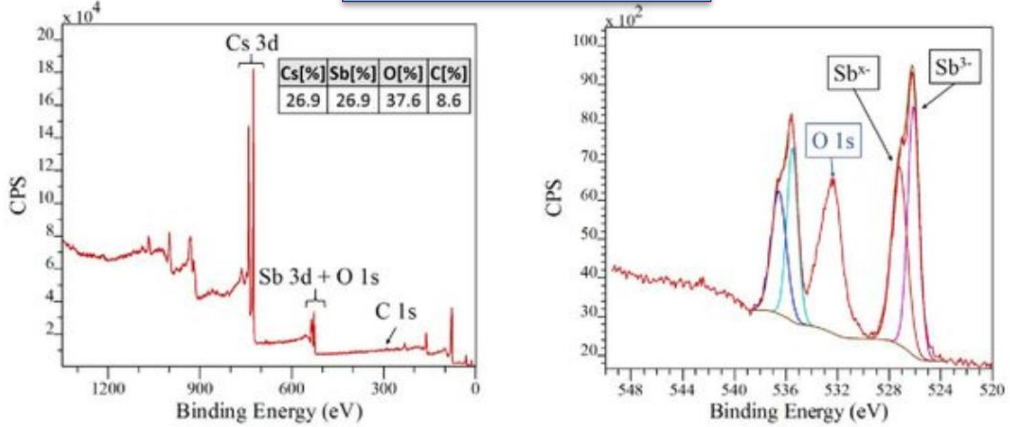




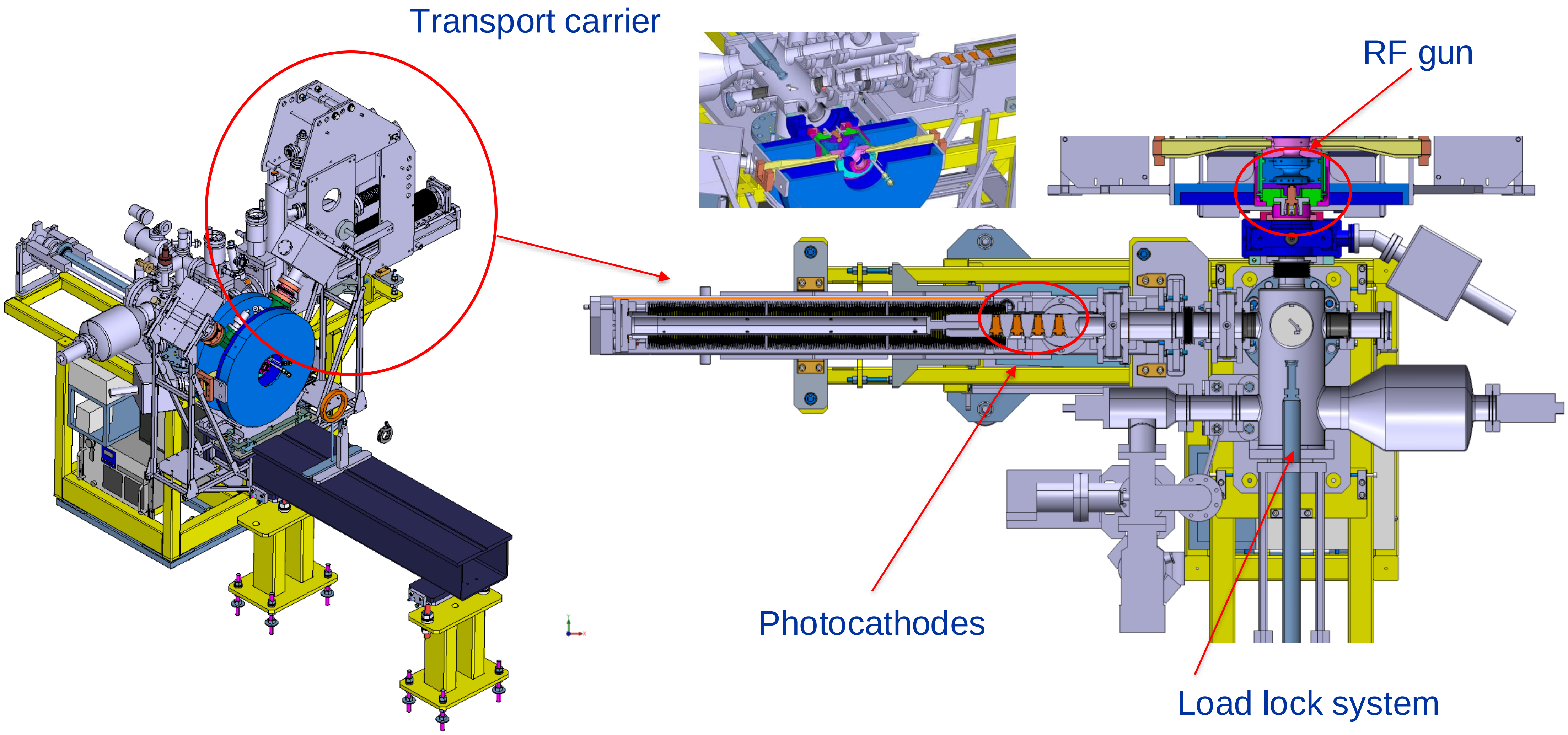
Fresh Photocathode



Used Photocathode



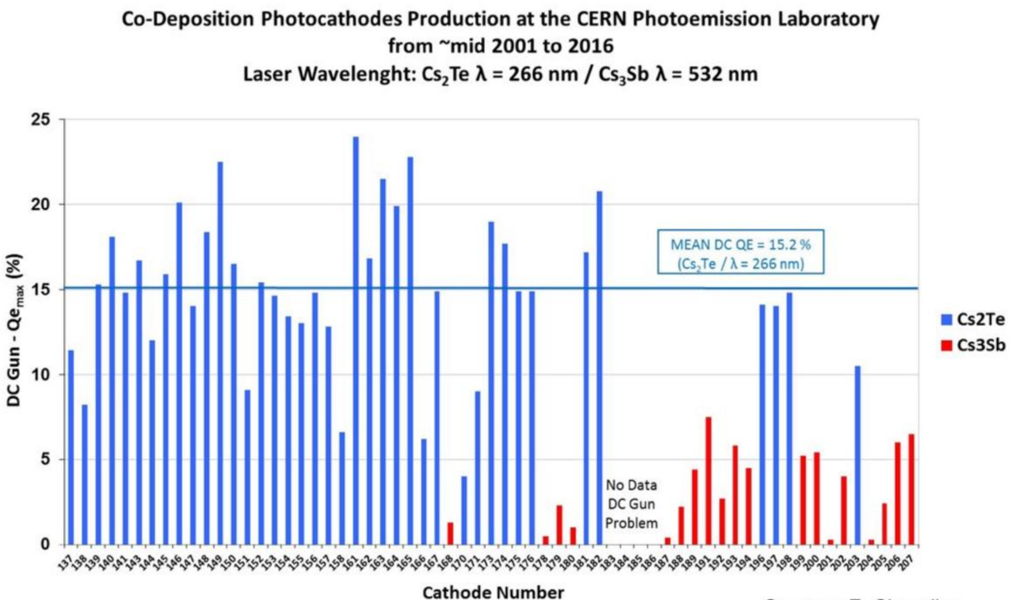
Photocathode transport and characterization (XPS)



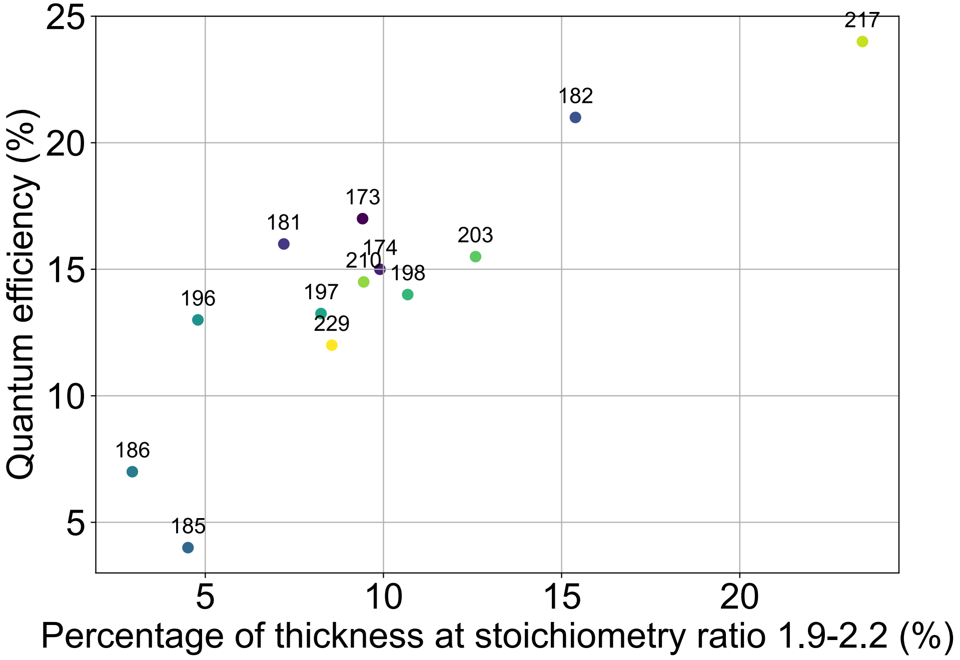
Re-analyzing 20 years' worth of photocathode growth data

To dig deeper into this analysis, we analyzed the thickness at different “windows” of the stoichiometric deposition ratio

We observe a clear trend when the “window” is narrowed to a range of 1.9 – 2.2. When the percentage of the total thickness at this “window” is higher, the measured QE also increases.



Courtesy E. Chevallay



Plasmonic photocathodes - Motivation

"The goal is to investigate such <u>surface-plasmon assisted photoemission</u> with a view on simplifying the photocathode production."

Current technology uses Cs_2Te photocathodes:

- Complex deposition fabrication process. Hard to achieve reliability.
- Requirements for UHV, limits lifetime of cathodes.
- Photocathode exchange process is complicated and slow, impacting operations.

The aim is to be able to use metallic cathodes for some injectors that don't require excessively large QE at CERN, avoiding semiconductors with all their disadvantages.

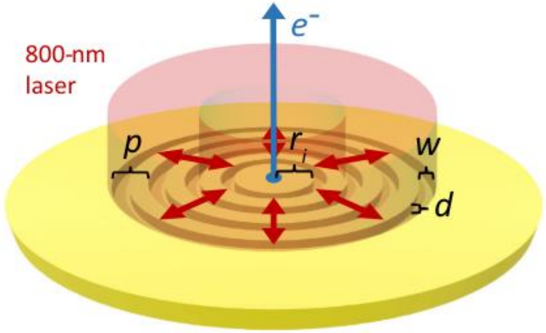
By-products:

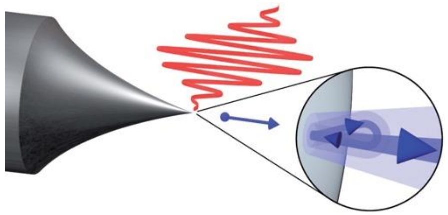
- Overall enhancement of QE for any photocathode technology.
- Possibility of spatially tailoring the emission characteristics of photocathodes via surface morphological features.

"The results of this project will have a positive impact for future projects at CERN (FCC, LHeC, etc) and beyond, such as for FLASH radiation therapy, FEL development and others."

The role of nanoscale photon-electron interactions

Electron sources and emitters

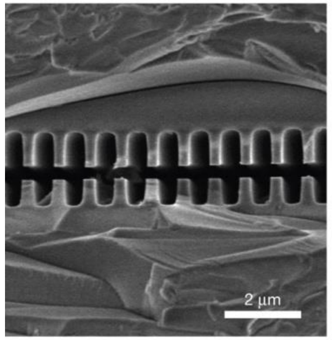


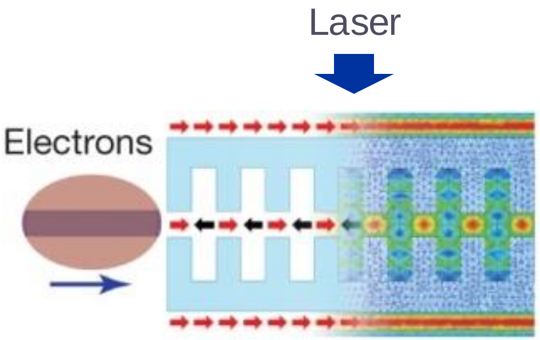


Phys. Rev. Applied 12, 054057 (2019)

Nature 475, 78–81 (2011)

Acceleration of charged particles

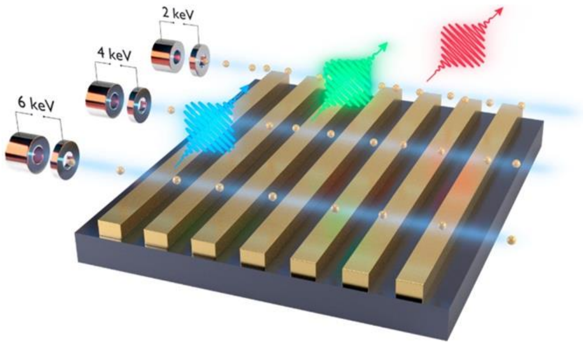


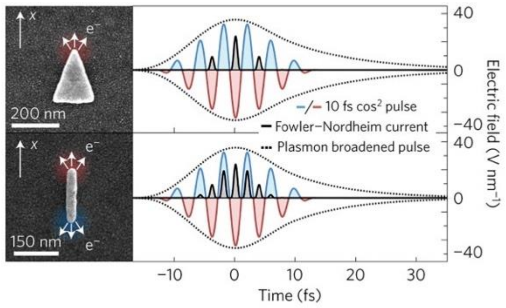


Nature 503, 91–94 (2013)

Nature 622 (7983), 476-480 (2023)

Diagnostics of electron and photon beams

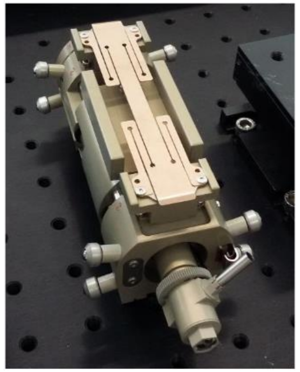




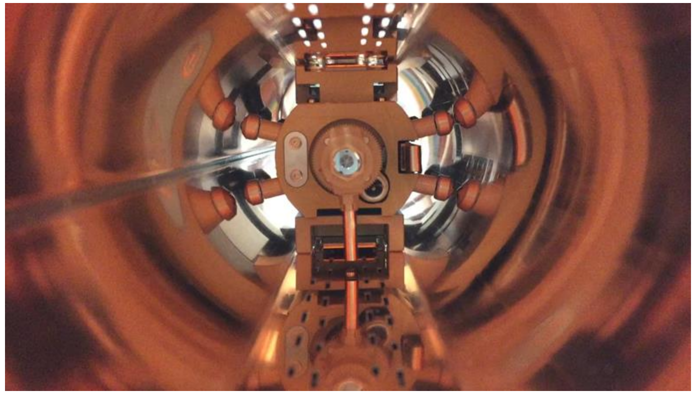
ACS Photonics **5**, 9, 3513-3518 (2018)

Nature Phys. **13**, 335–339 (2017)

Mitigation of secondary electron effects



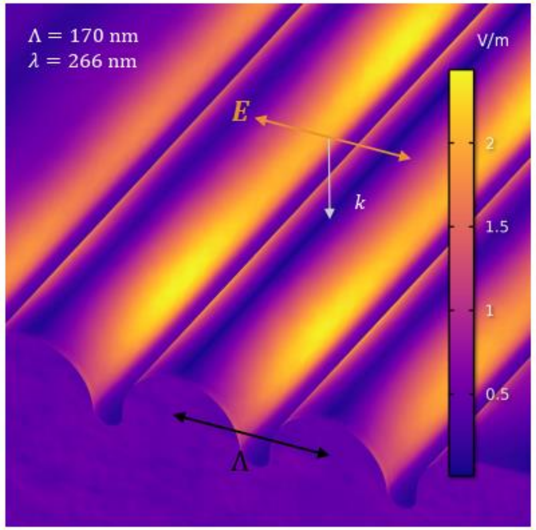
LESS robot

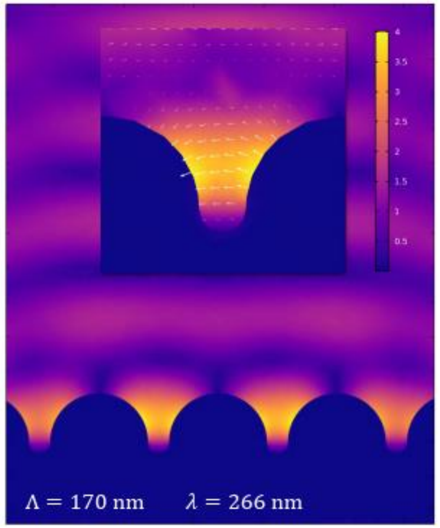


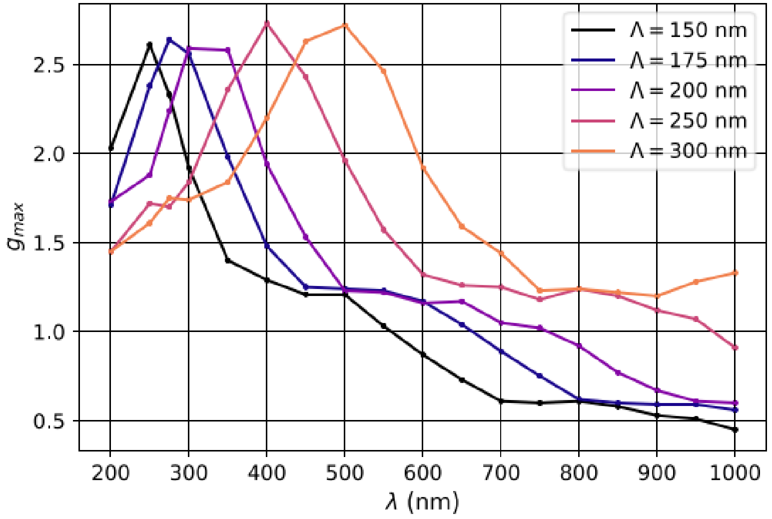
Laser treatment at the Large Hadron Collider

Simulation of plasmonic effects in nanostructured metals

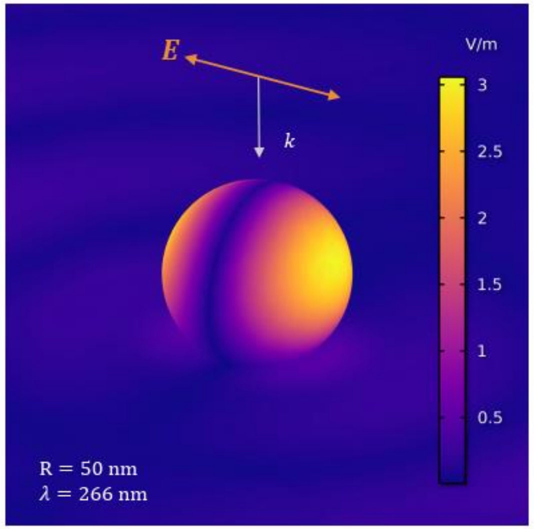
"LIPSS"

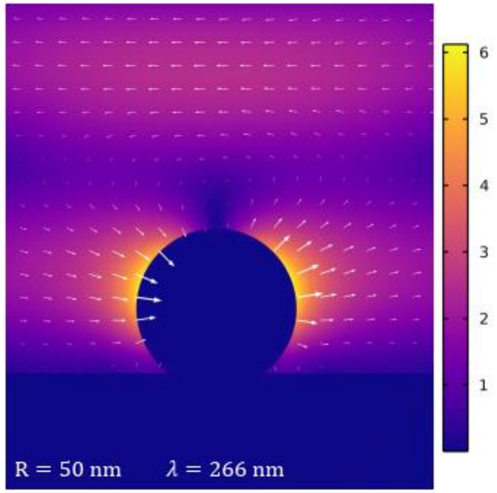


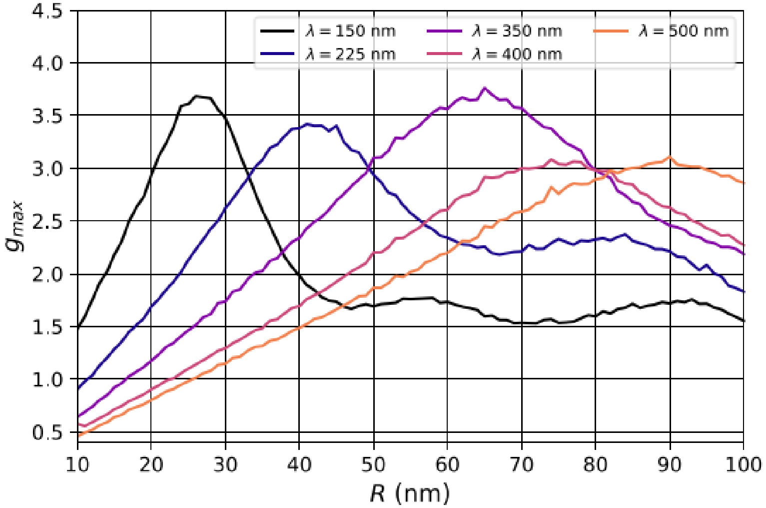




"spheres"

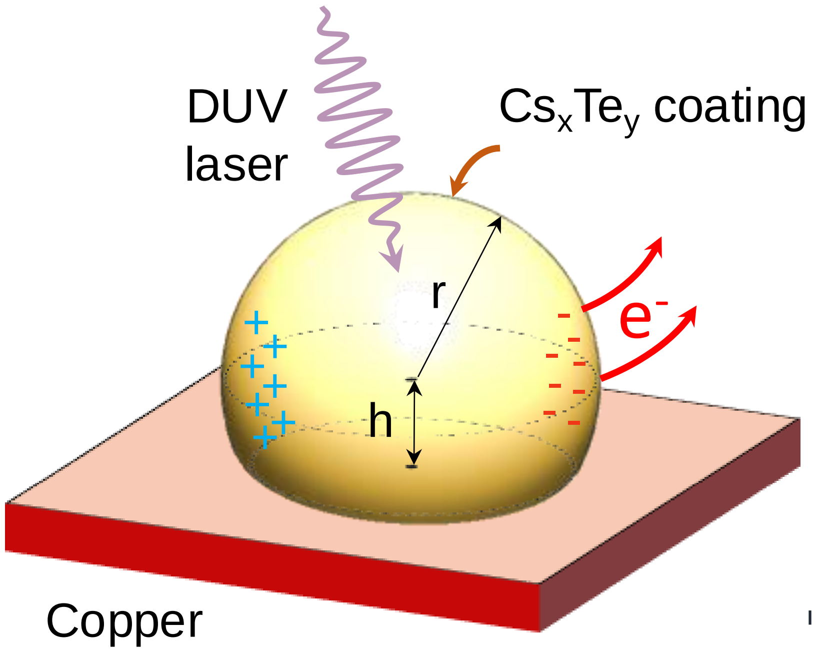


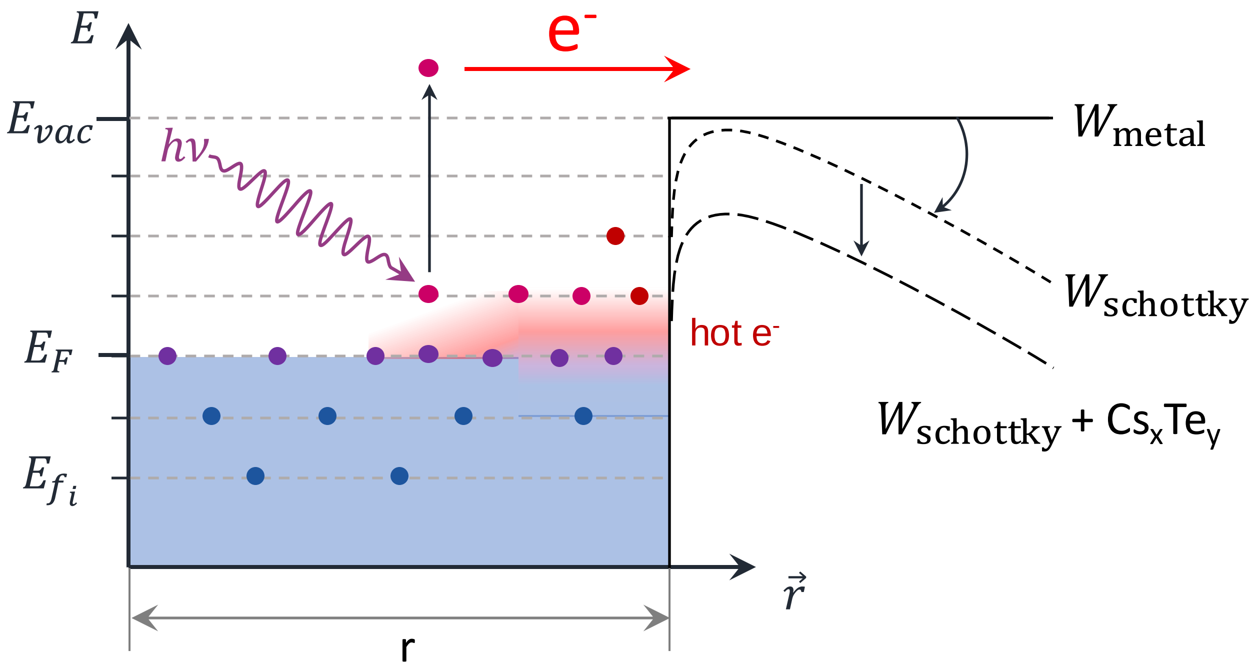




B. Groussin, et al. "Simulation of Plasmonic Effects in Nanostructured Copper Surfaces for Field-assisted photoemission" *Journal of Physics: Conference Series*, vol. **2687**, no. 032034 (2024)

Hot electron emission from nanospheres

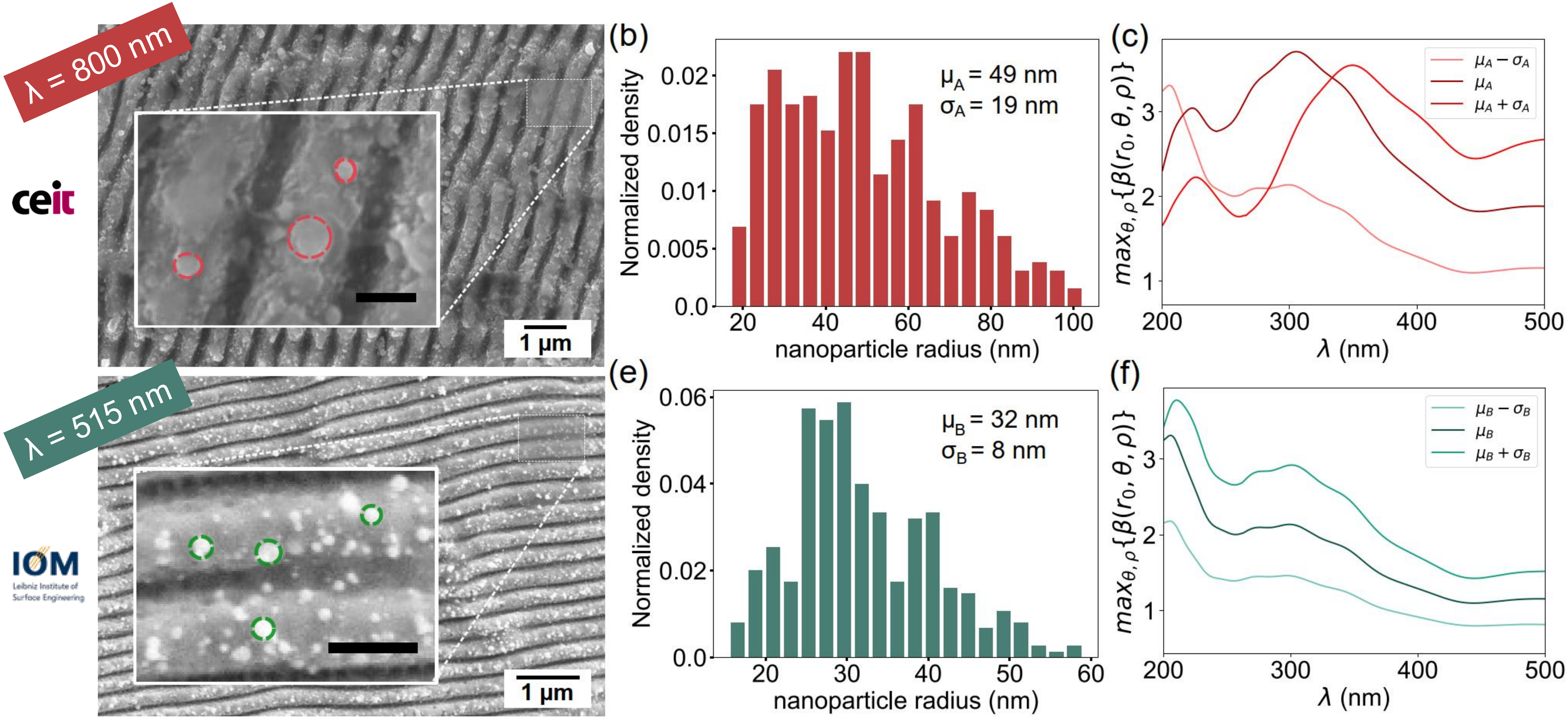




- The work function (W) for most metals is in the DUV wavelength range (200-250 nm)
- Spheres are well suited for moderate field enhancements and electron temperature, preventing LIDT
- Easy to regenerate in-situ.

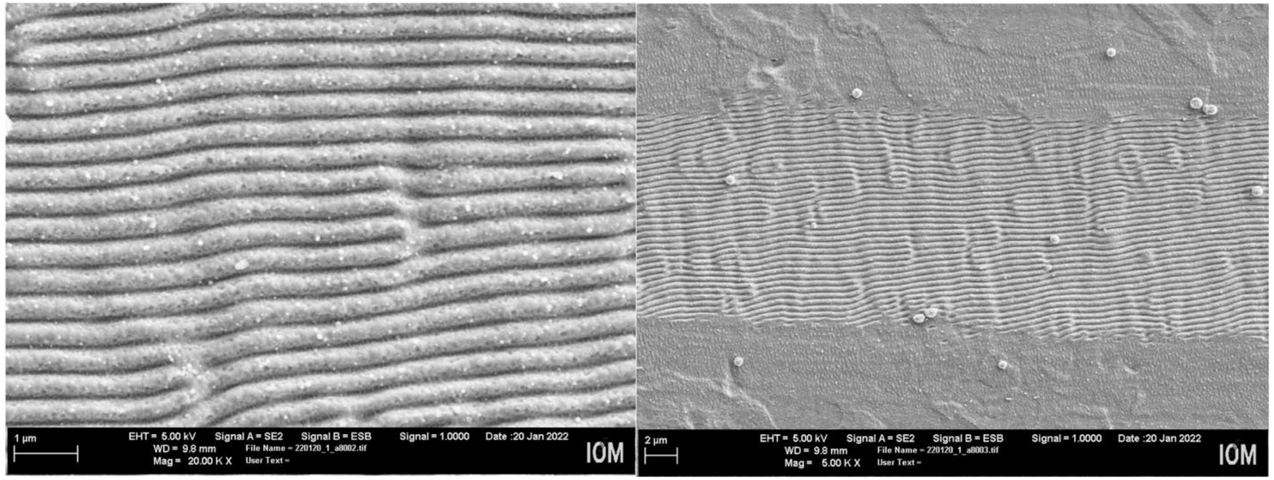
M. Martinez-Calderon, et al. "Hot electron enhanced photoemission from laser fabricated plasmonic photocathodes" *Nanophotonics*, vol. **13**, no. 11, pp. 1975-1983 (2024)

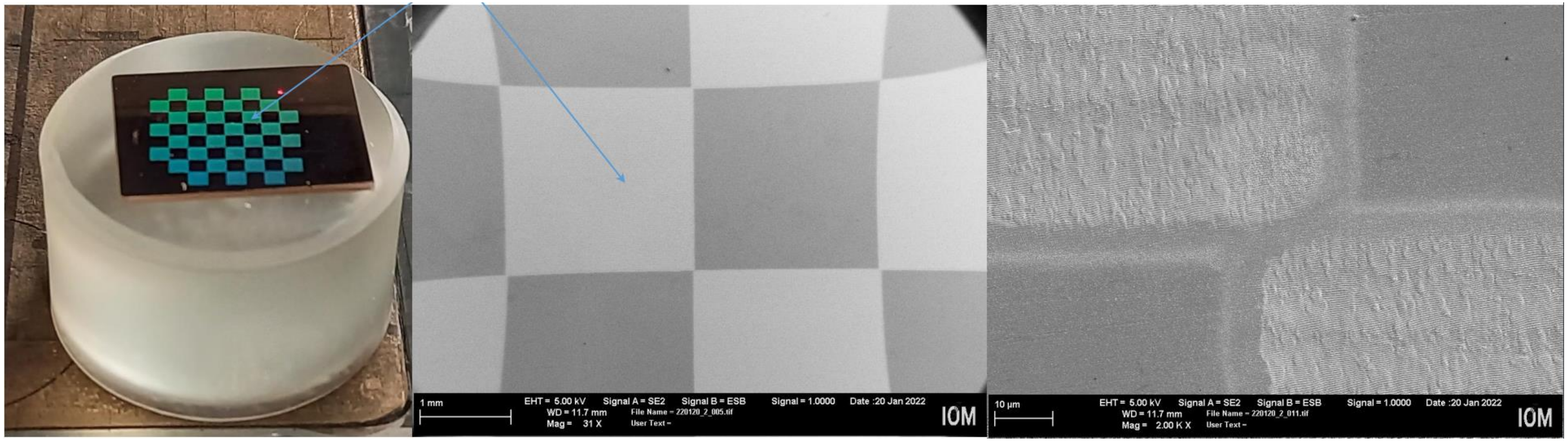
Nanosphere size distribution for each photocathode



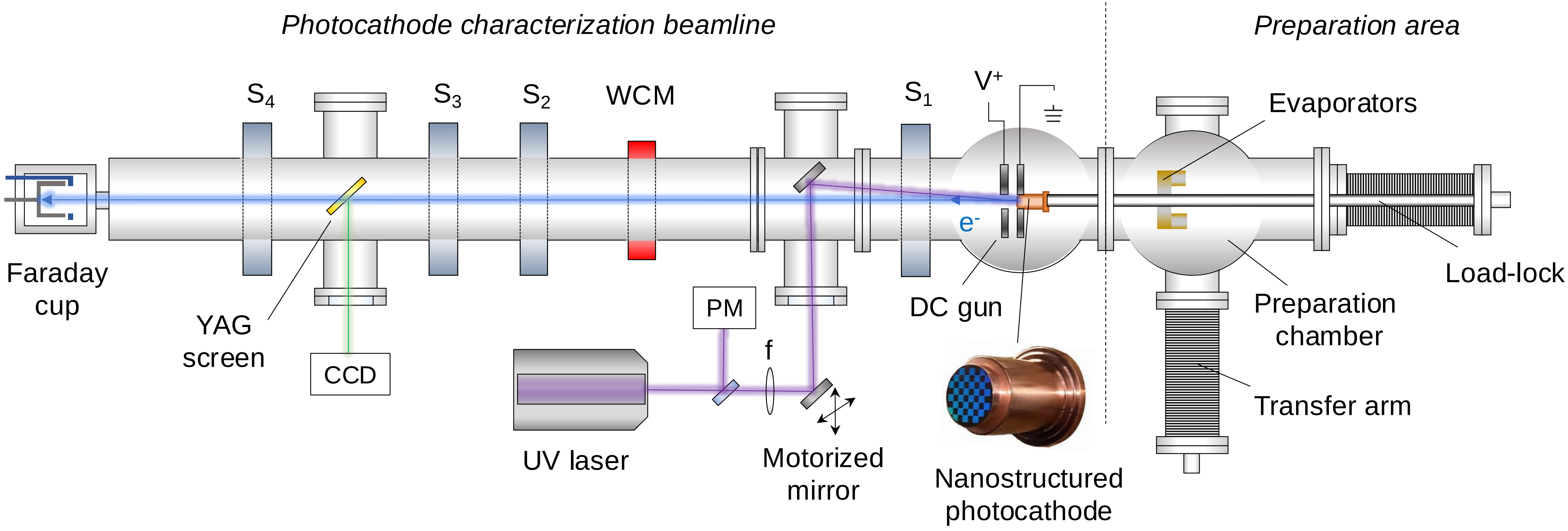
M. Martinez-Calderon, et al. "Hot electron enhanced photoemission from laser fabricated plasmonic photocathodes" *Nanophotonics*, vol. **13**, no. 11, pp. 1975-1983 (2024)

Laser fabricated plasmonic photocathodes





Performance of laser-produced plasmonic photocathodes



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Nanophotonics, vol. **13**, no. 11, pp. 1975-1983 (2024)

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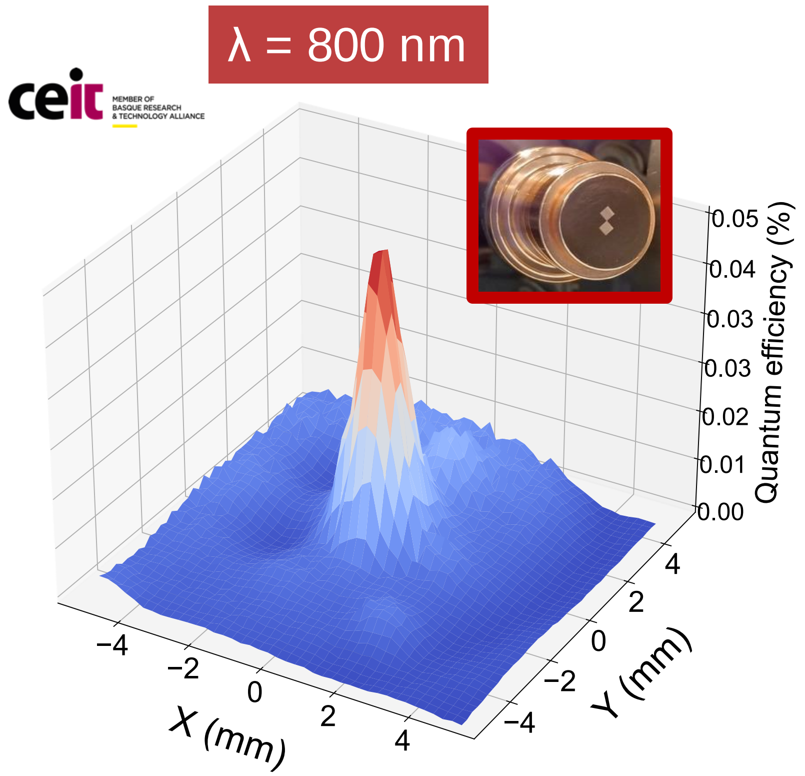
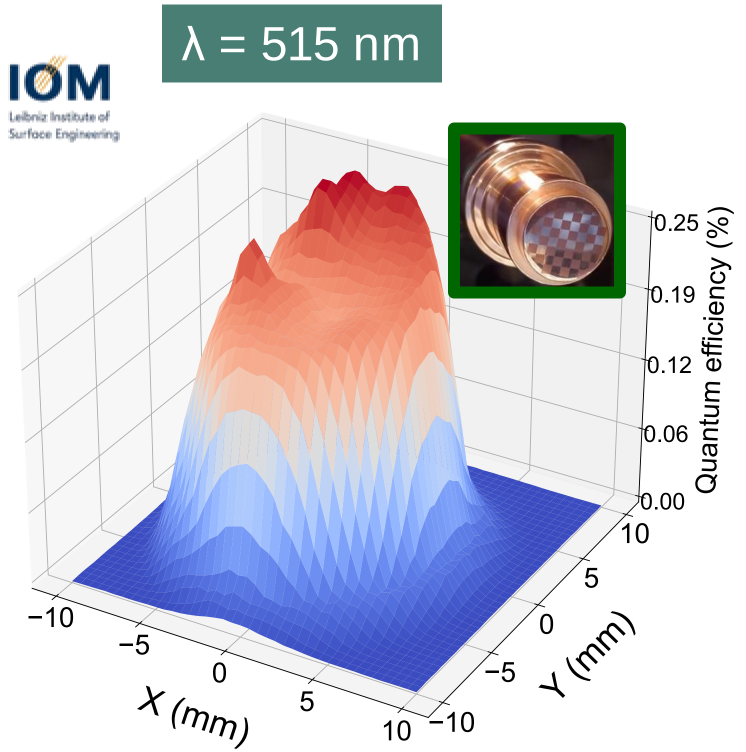
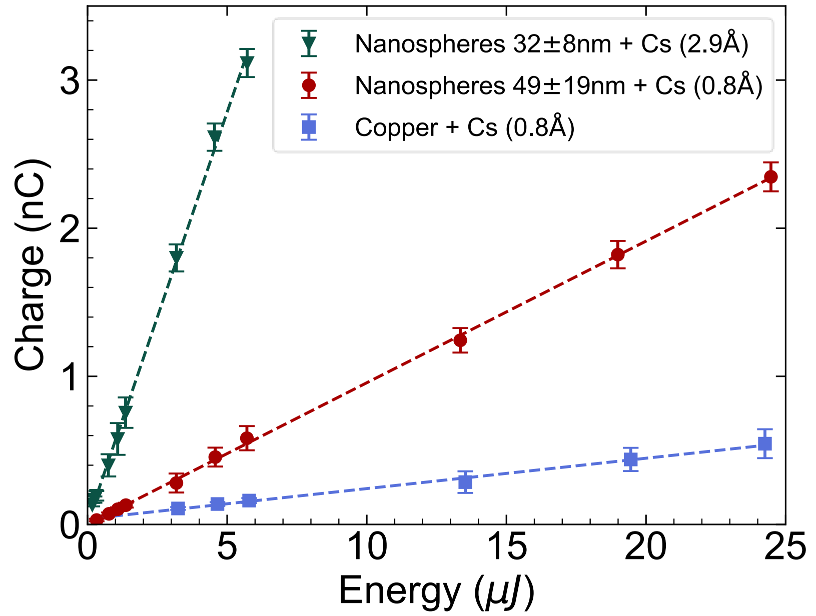


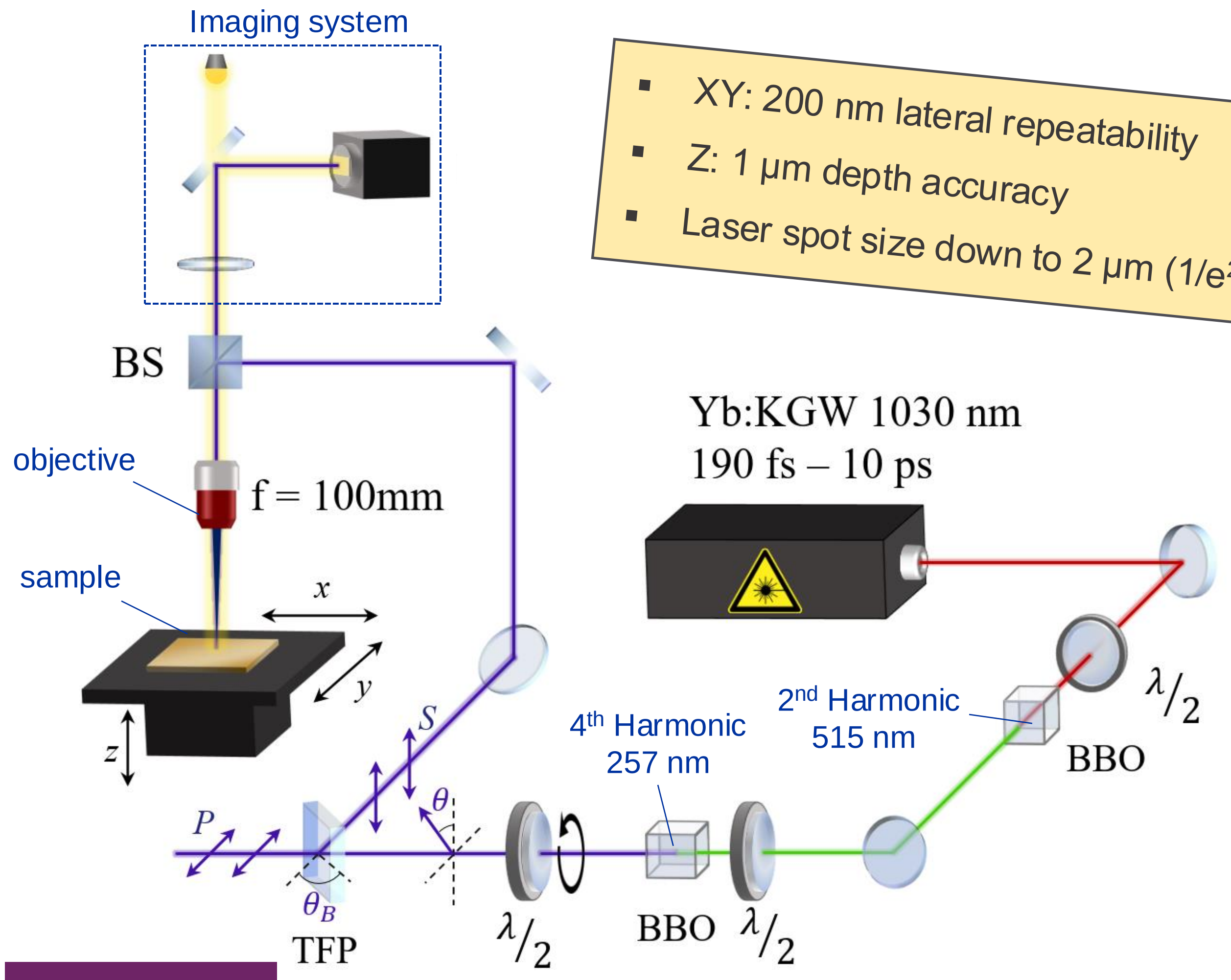




- CEIT's photocathode shows consistent spatial distribution, but only 5x enhancement
- IOM's photocathode: wasn't possible to spatially resolve the checkerboard, but 25x enhancement
- Assessment of surface composition was realized with XPS, pointing at oxidation issues during laser treatment

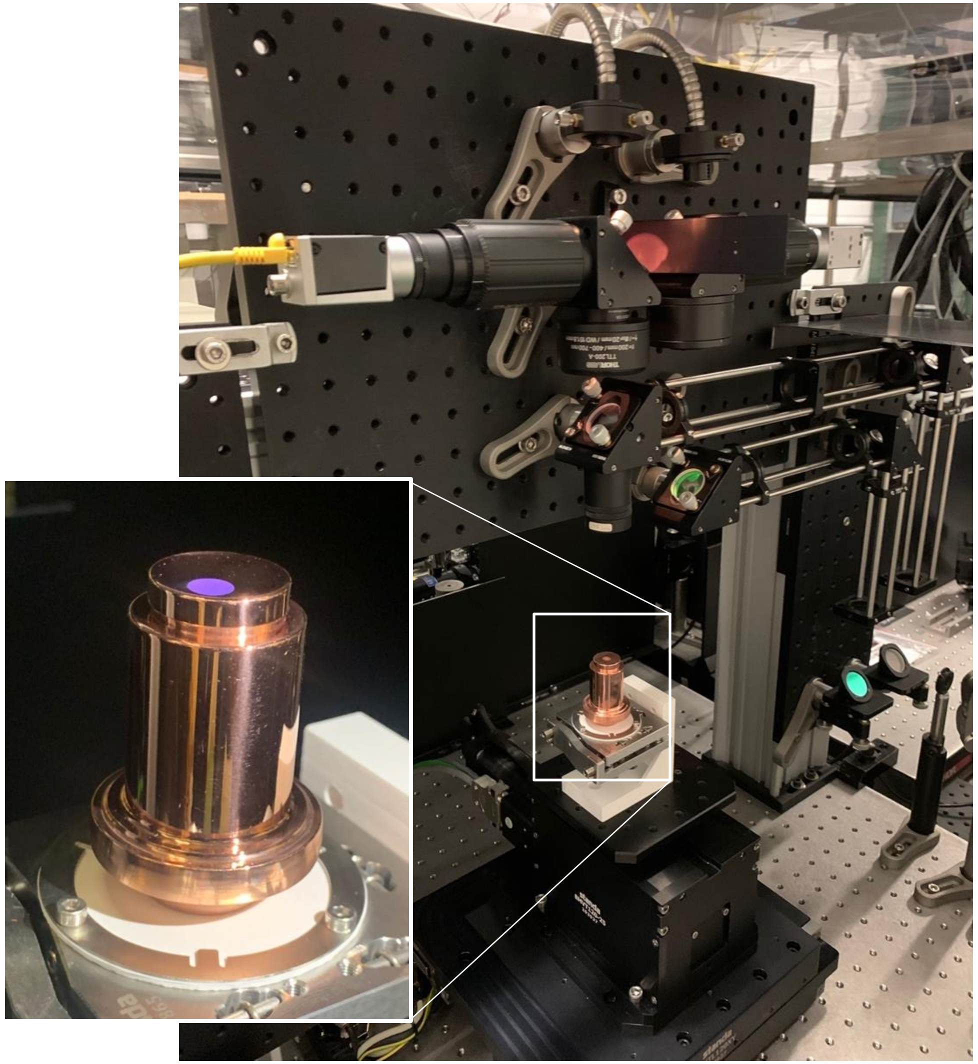
M. Martinez-Calderon, et al. "Hot electron enhanced photoemission from laser fabricated plasmonic photocathodes"
Nanophotonics, vol. **13**, no. 11, pp. 1975-1983 (2024)

Laser nanomachining station at CERN

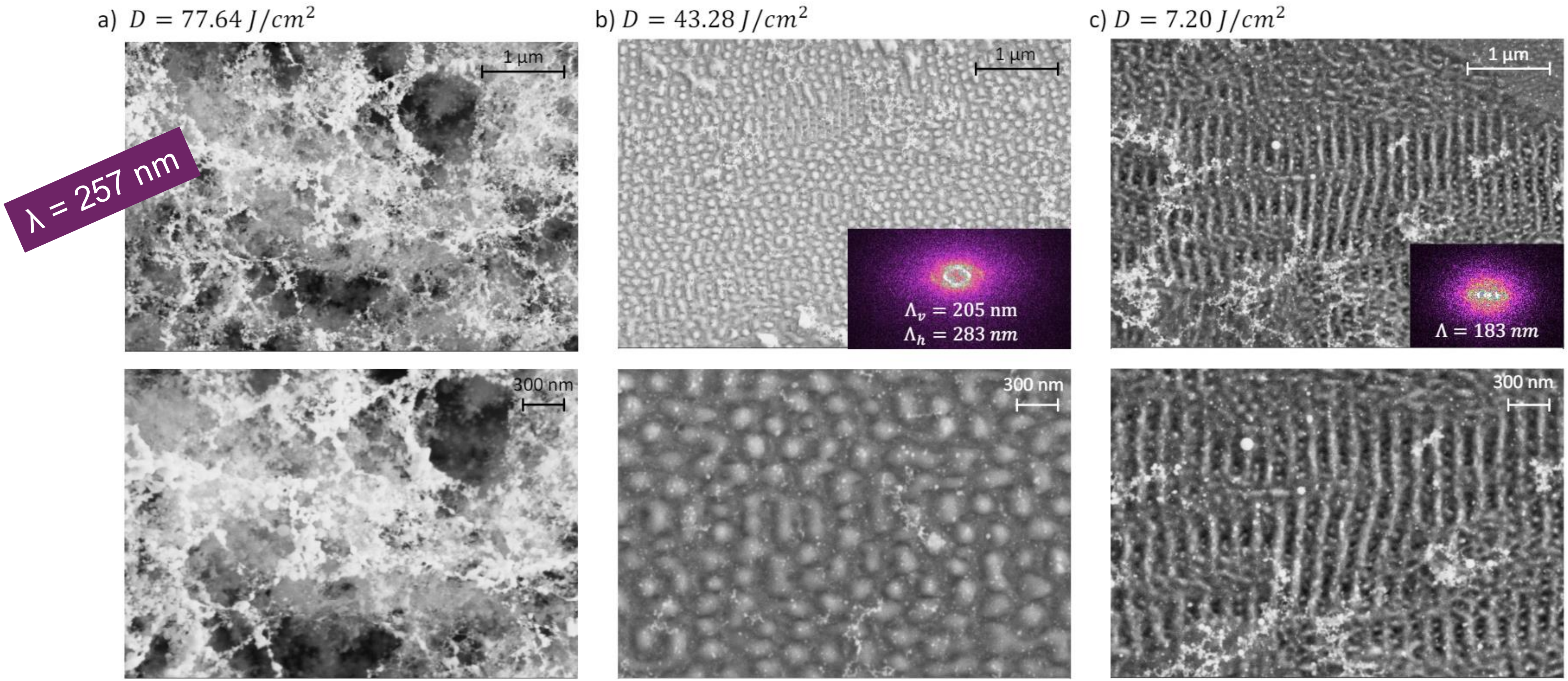


- XY: 200 nm lateral repeatability
- Z: 1 μm depth accuracy
- Laser spot size down to 2 μm ($1/e^2$)

λ = 257 nm

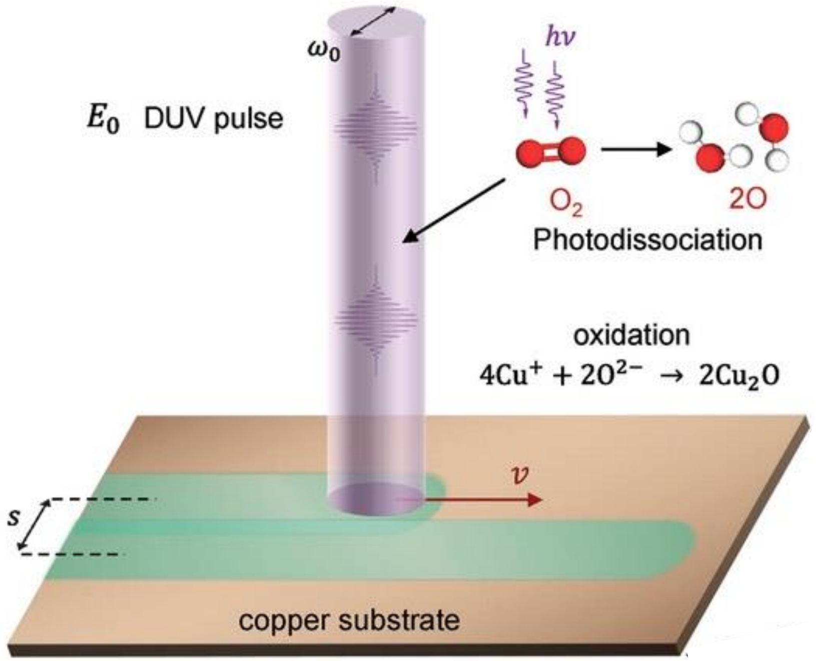


In general, very heterogeneous results with 257 nm



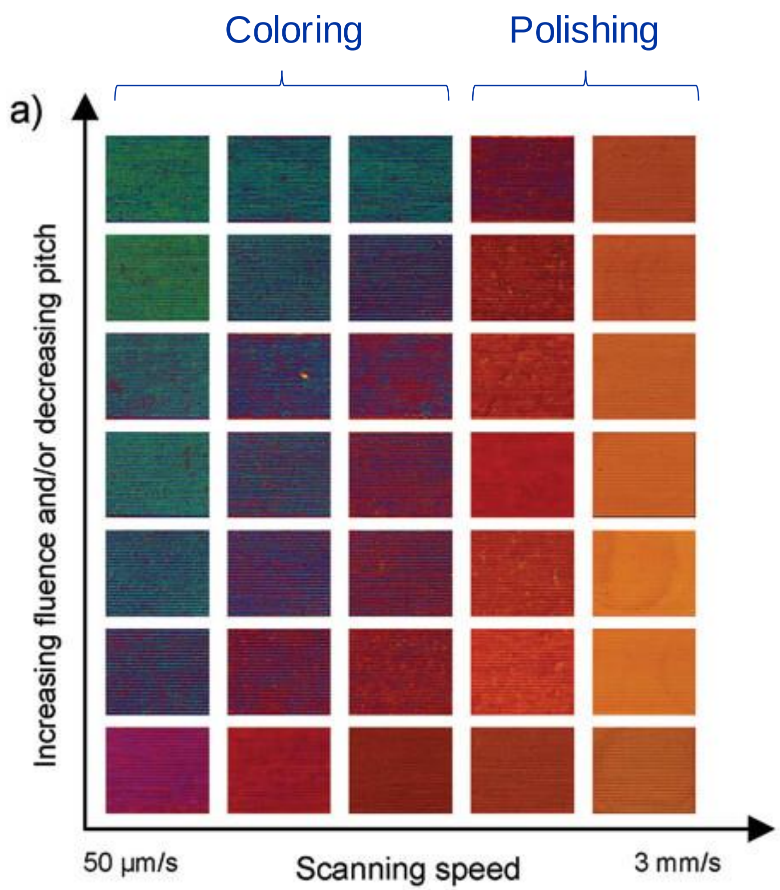
B. Groussin, et al. “Copper Surface Treatment with deep UV Ultrafast Laser for Improved Photocathode Photoemissive Properties" *Journal of Physics: Conference Series*, vol. **2687**, no. 032032 (2024)

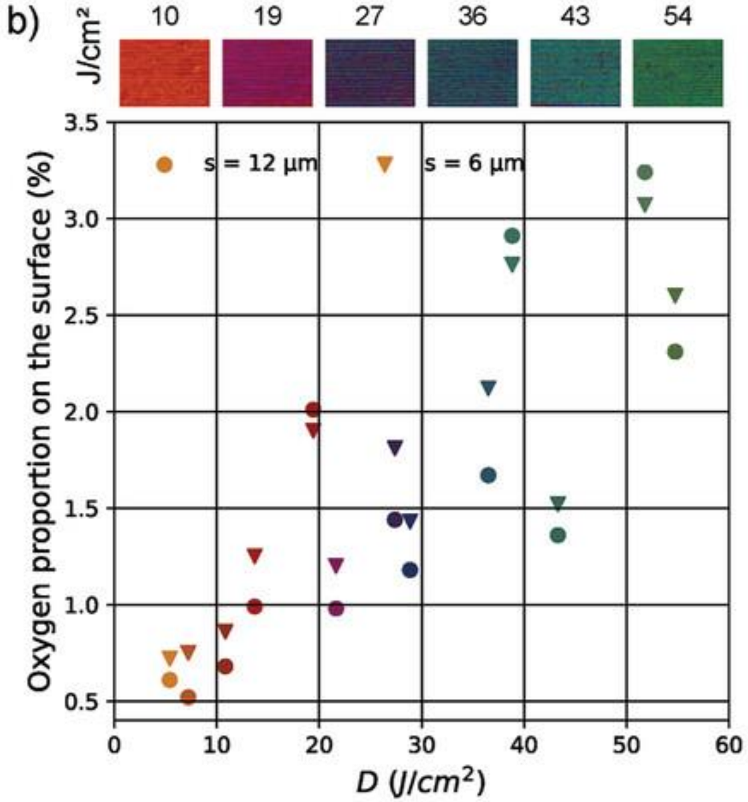
Highly efficient copper oxidation with DUV laser

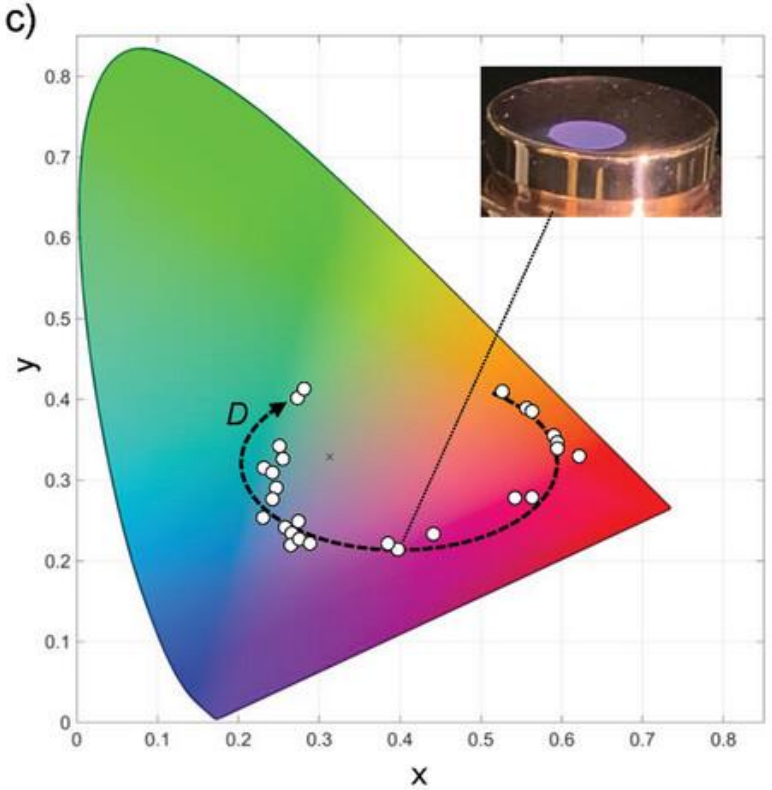


B. Groussin, et al. "Efficient Composite Colorization of Copper by Spatially Controlled Oxidation with Deep-UV Ultrafast Lasers" *Advanced Optical Materials*, vol. **12,** no. 2302071 (2024)

Highly efficient copper oxidation with DUV laser





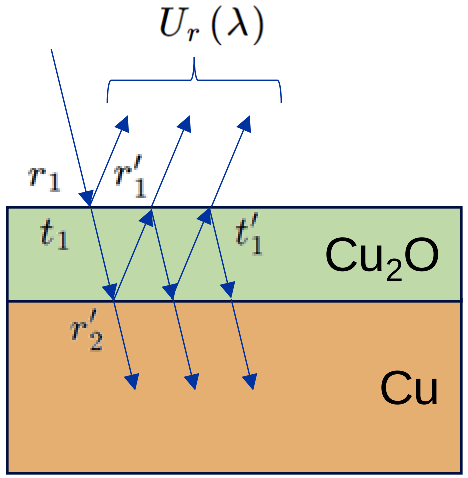


$$D = F_0 \times N = \frac{E_0}{\pi \omega_0^2} \times \frac{f_{\text{rep}}\, 2\omega}{v}$$

B. Groussin, et al. “Efficient Composite Colorization of Copper by Spatially Controlled Oxidation with Deep-UV Ultrafast Lasers" *Advanced Optical Materials*, vol. **12,** no. 2302071 (2024)

Highly efficient copper oxidation with DUV laser

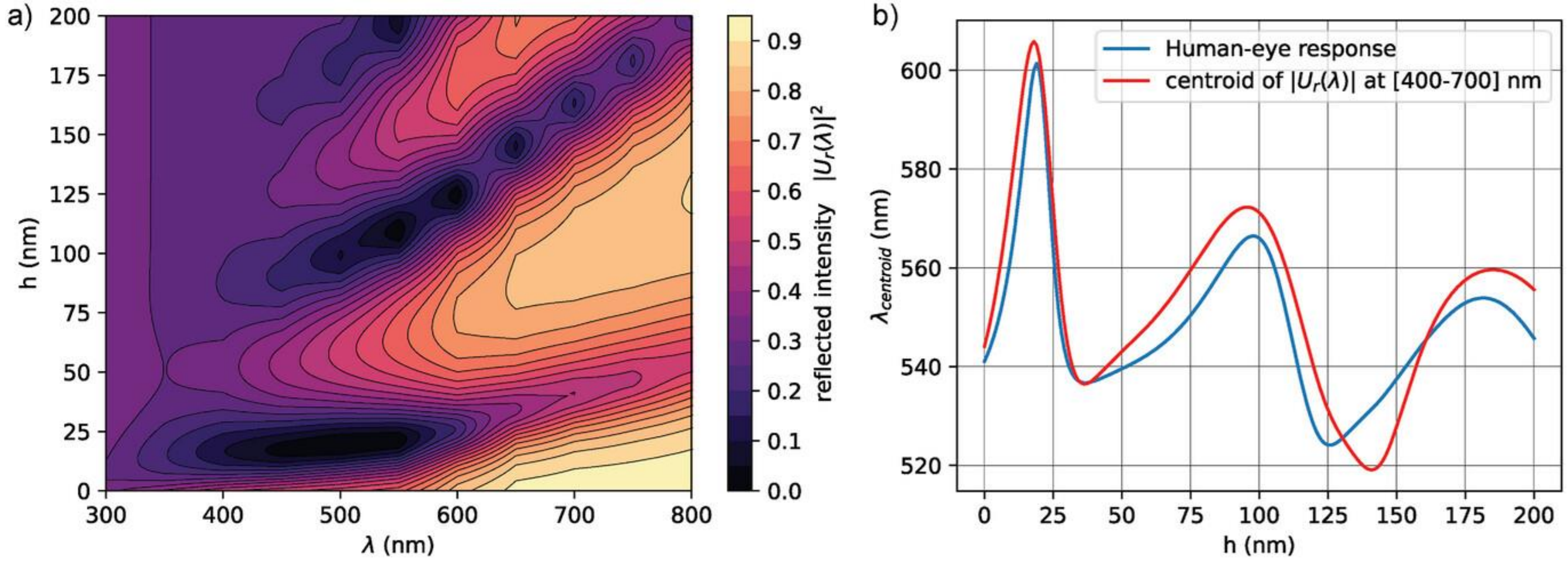
Thin oxide film reflectivity



$$U_r(\lambda) = r_1 + \frac{t_1 t_1' r_2' e^{i\phi}}{1 - r_1' r_2' e^{i\phi}}$$

$$\phi = 4\pi\nu \frac{n_0(\lambda)\, h}{c} \cos(\theta)$$

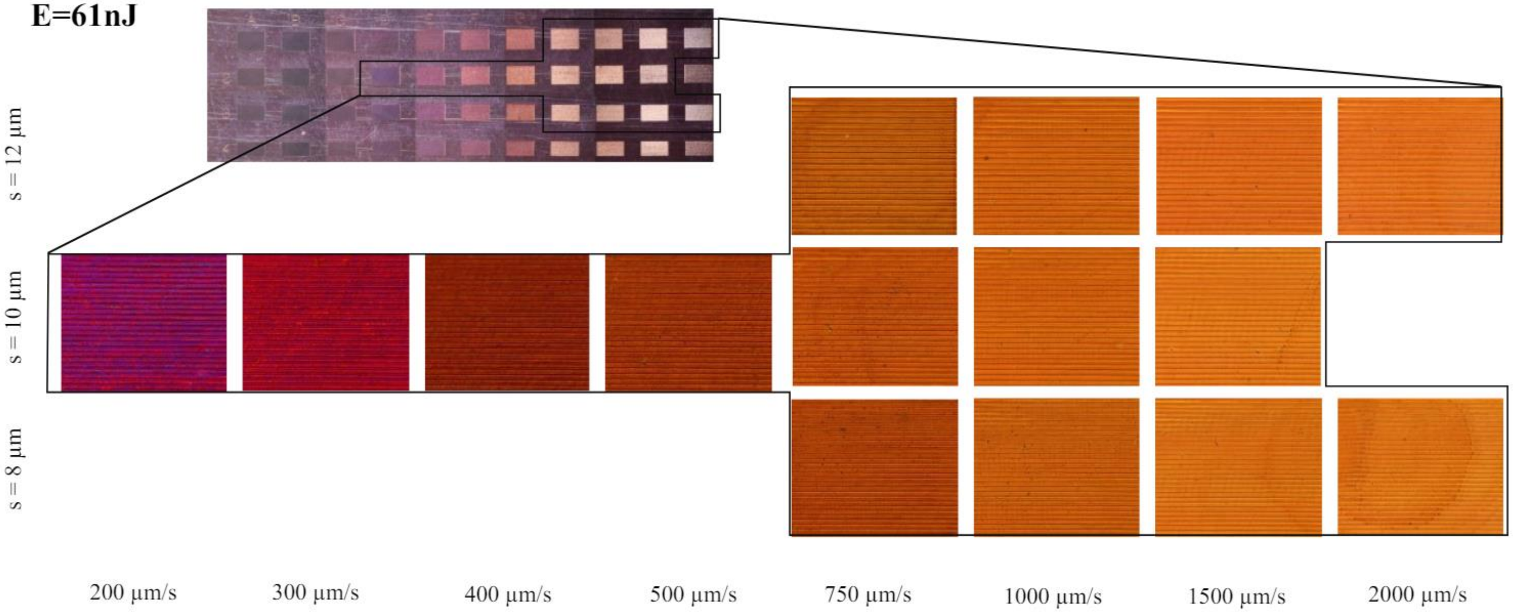
r, *t* are complex in general

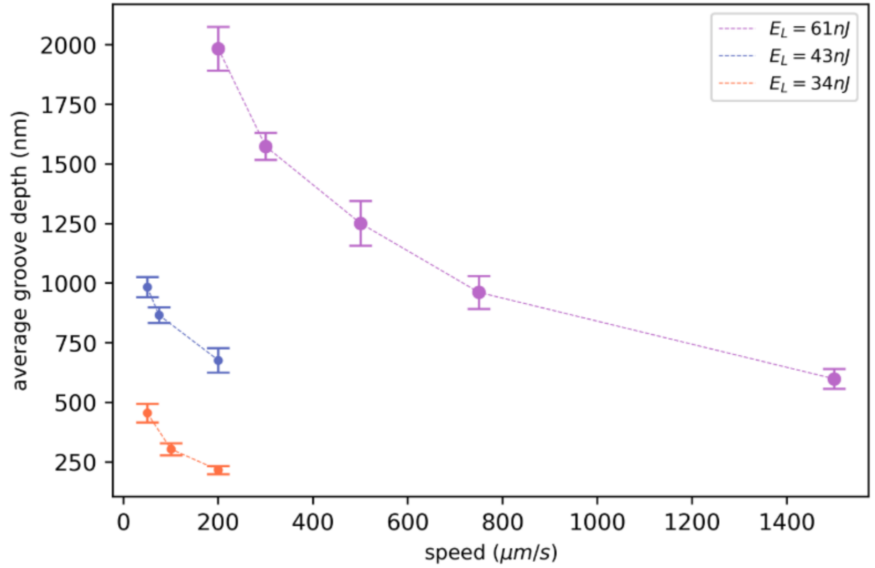


- Centroid of reflected spectrum perdiocally shifts with oxide thickness
- Absorption eventually makes the spectrum converge to typical green oxide.
- Weighiting in the human eye response a similar trend is observed, consistent with experiments.

B. Groussin, et al. “Efficient Composite Colorization of Copper by Spatially Controlled Oxidation with Deep-UV Ultrafast Lasers" *Advanced Optical Materials*, vol. **12,** no. 2302071 (2024)

Machining of copper with nm resolution

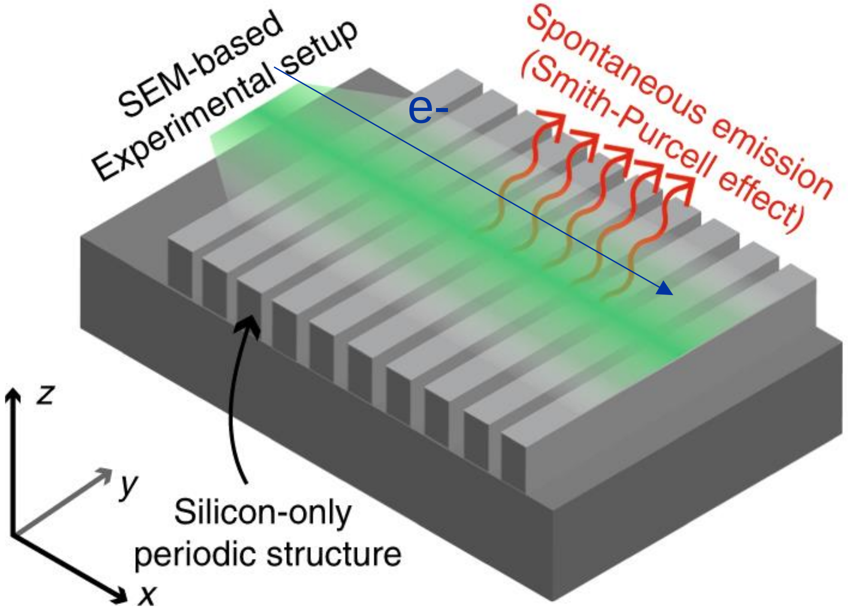


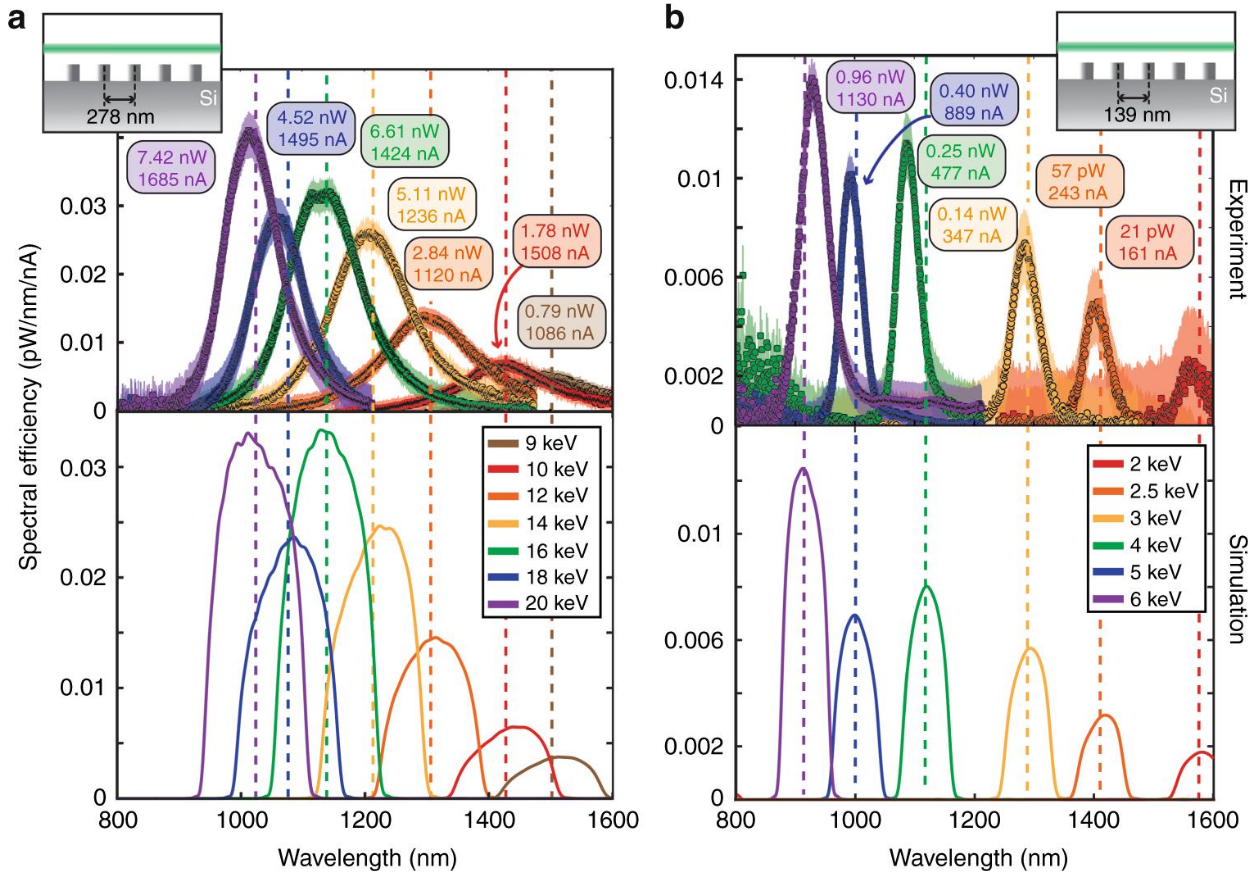


- Good prospects for nanomachining of copper with 10s of nm accuracy
- Oxygen content depends mostly on integrated dose *D*, whereas machining depth is more correlated to laser fluence.
- Possibility of 'erasing' colors by rastering laser at high speed over the surface.

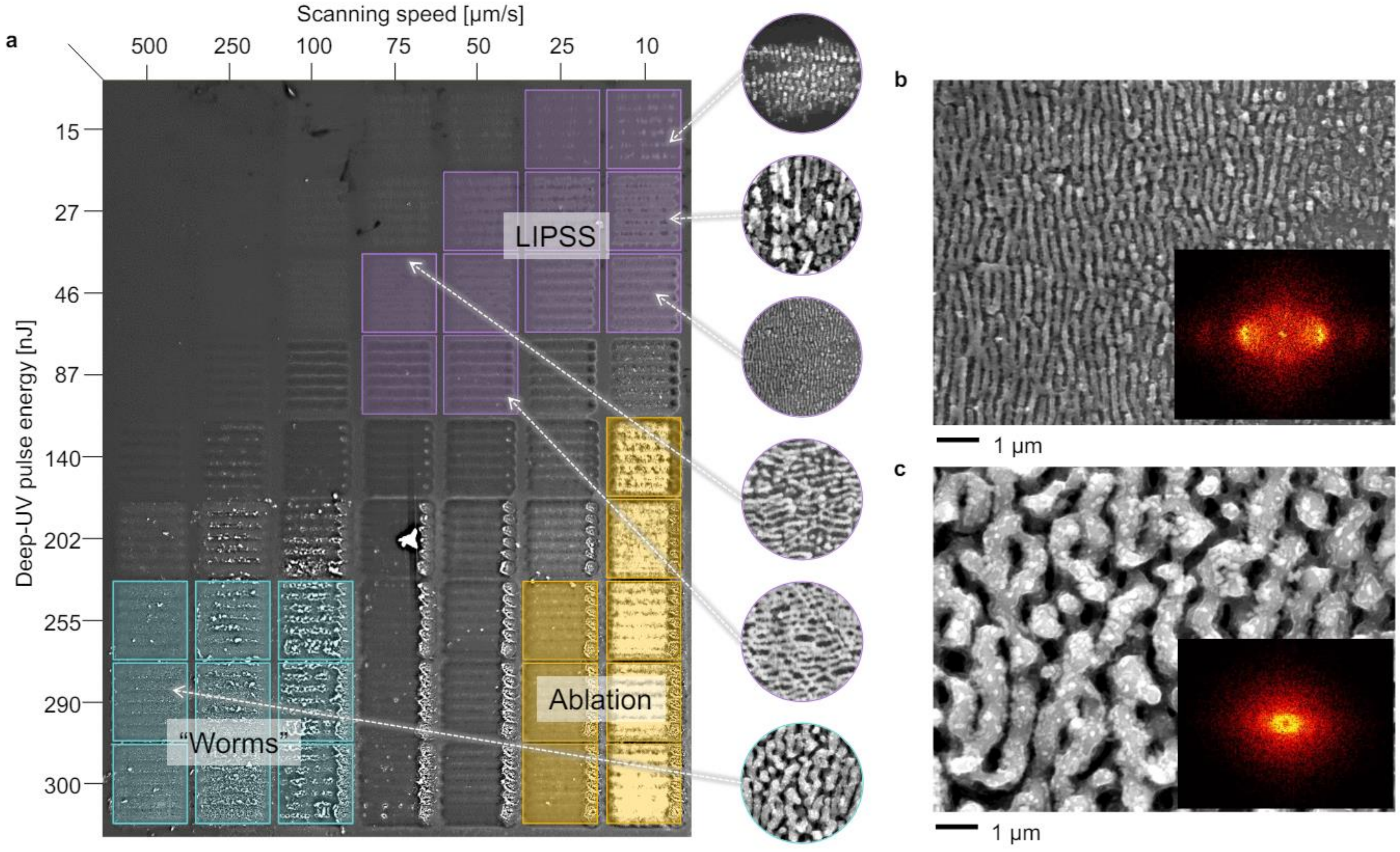
B. Groussin, et al. "Efficient Composite Colorization of Copper by Spatially Controlled Oxidation with Deep-UV Ultrafast Lasers" *Advanced Optical Materials*, vol. **12,** no. 2302071 (2024)

Silicon free-electron light sources





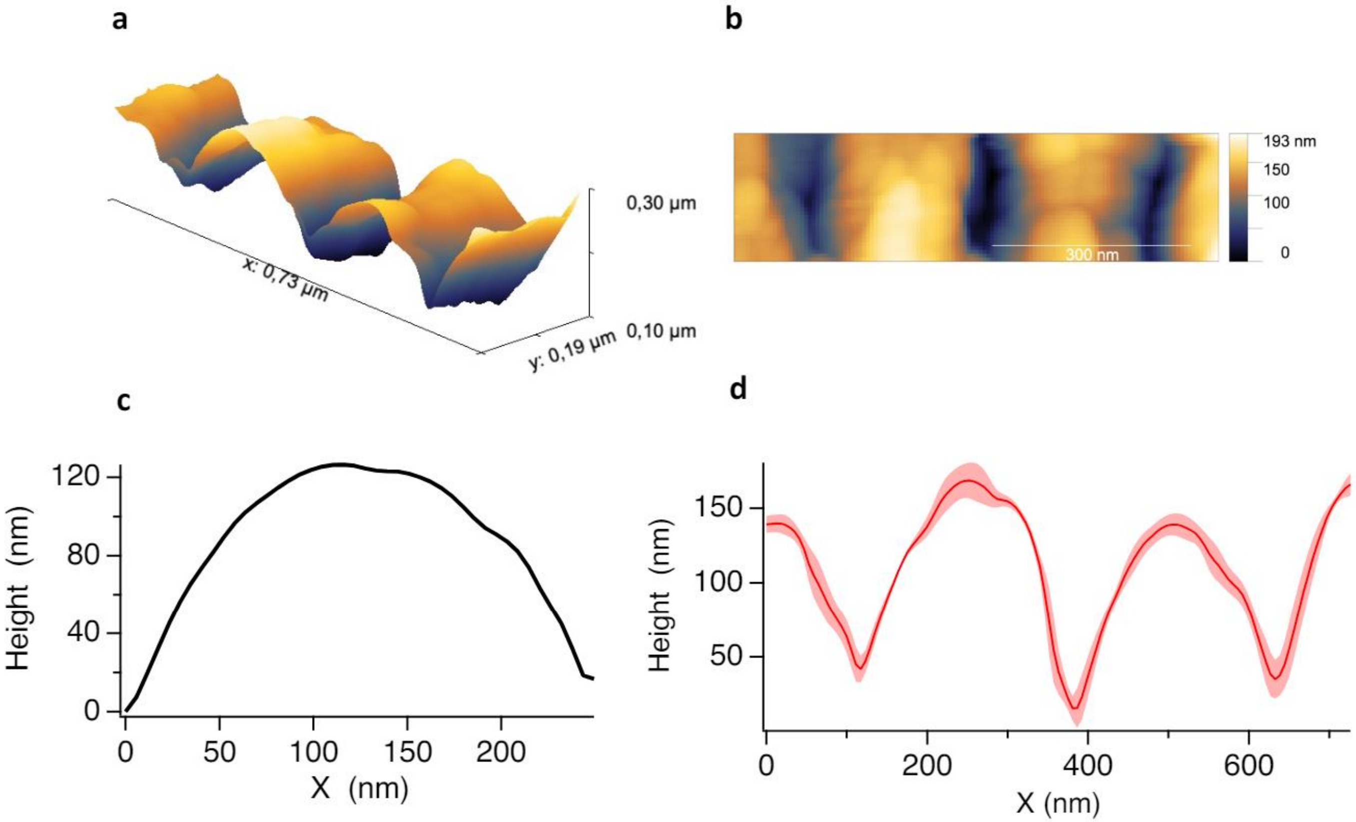
High aspect ratio Silicon nanostructures using DUV pulses



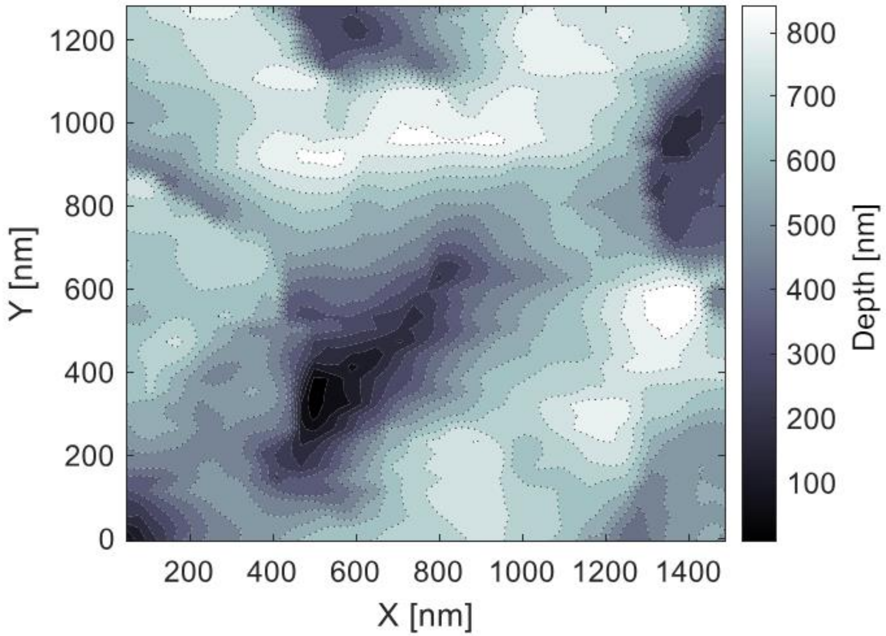
E. Granados. *et al.* "Highly Uniform Silicon Nanopatterning with deep-ultraviolet femtosecond pulses", *Nanophotonics* (2024)
https://doi.org/10.1515/nanoph-2024-0240

High aspect ratio Silicon nanostructures using DUV pulses

LIPSS



Worms



CIC nanoGUNE
MEMBER OF BASQUE RESEARCH & TECHNOLOGY ALLIANCE

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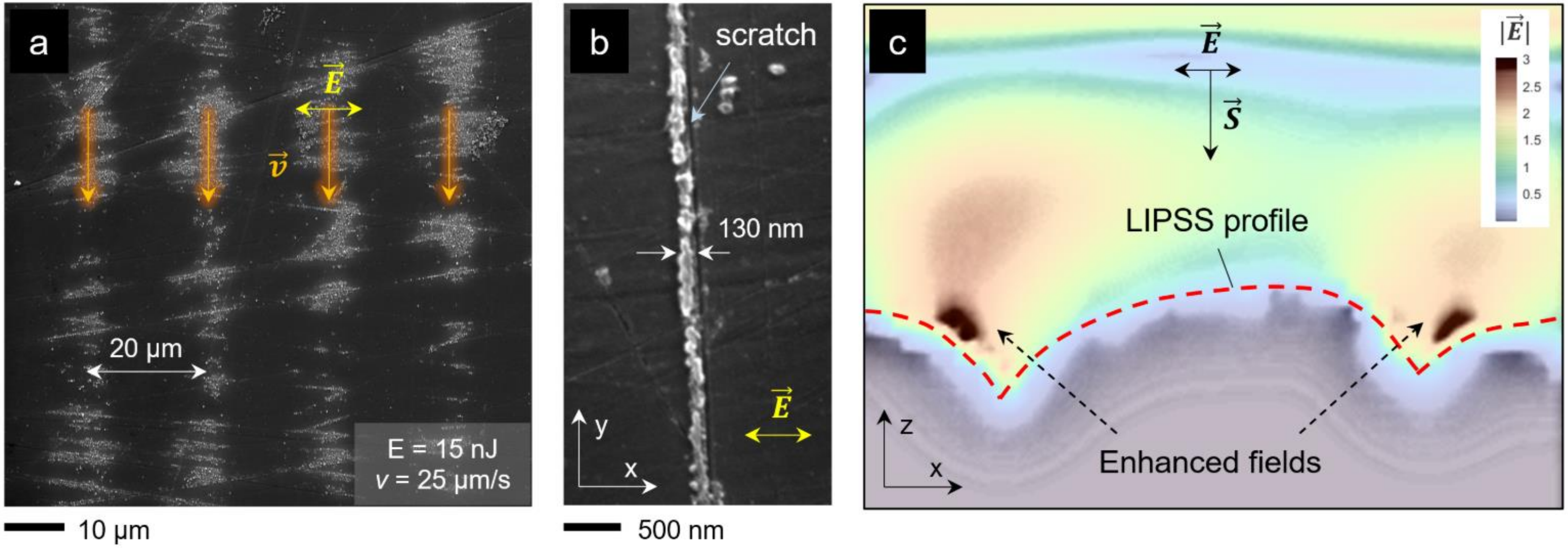

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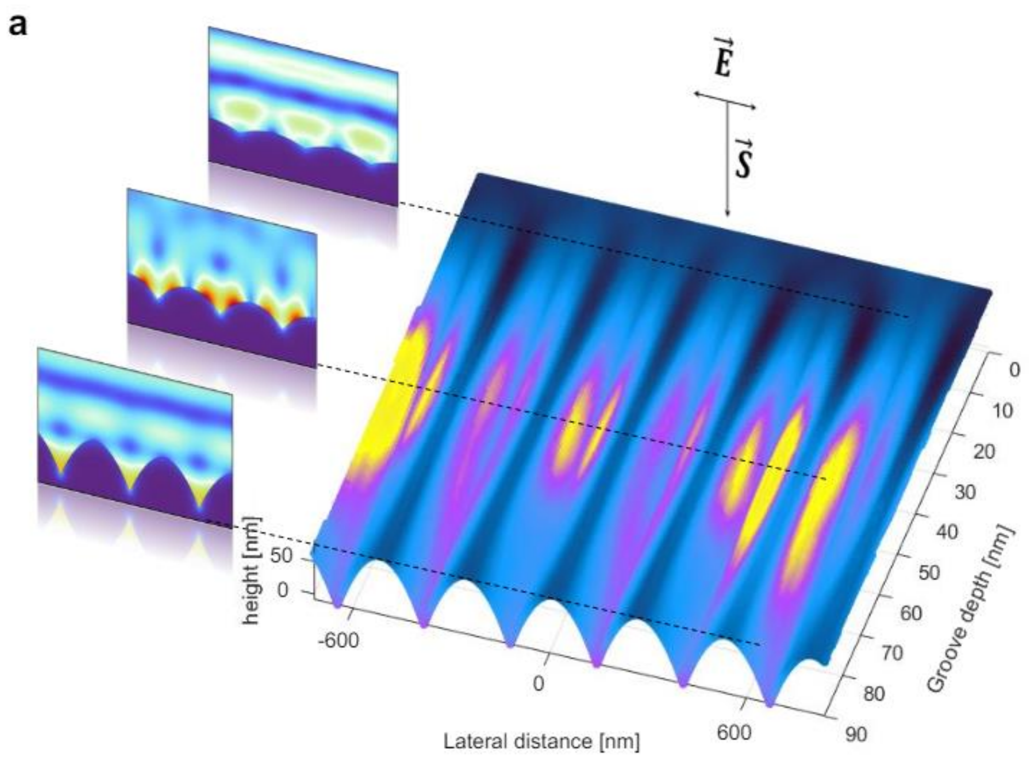

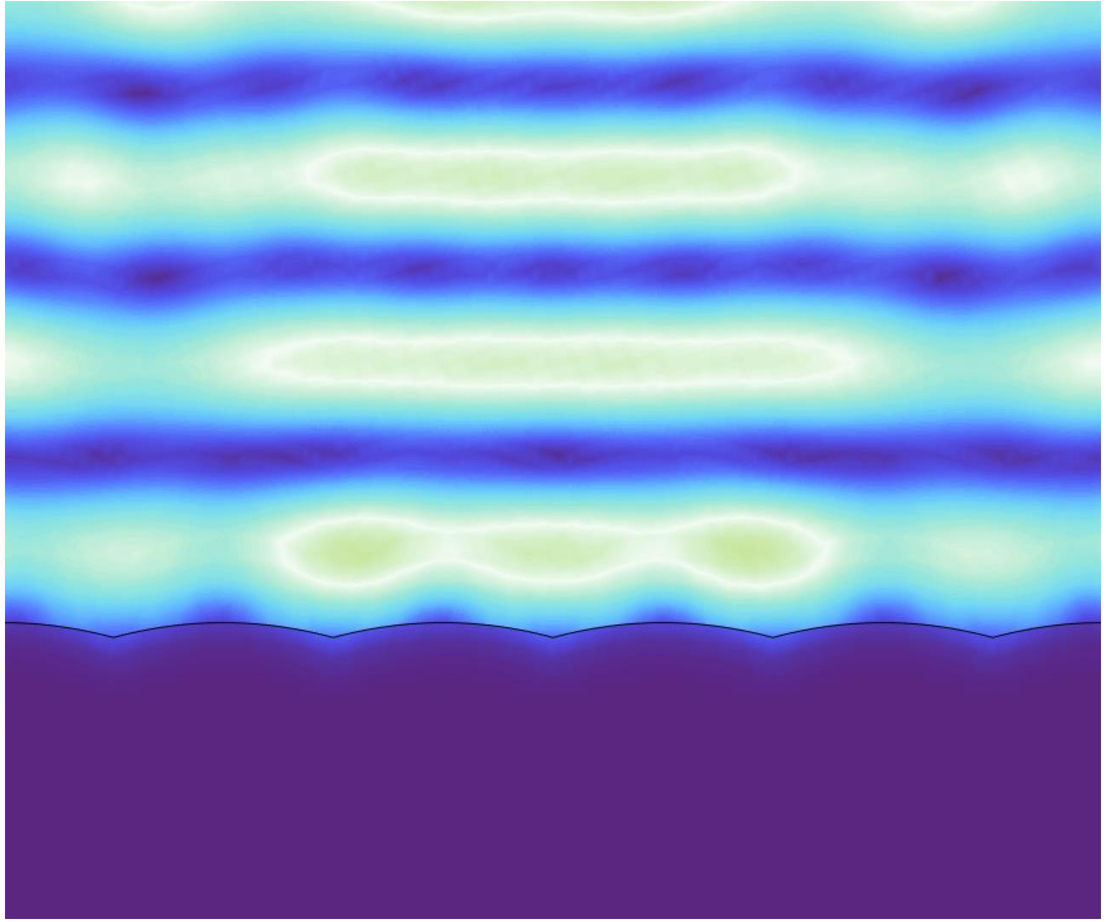

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https://doi.org/10.1515/nanoph-2024-0240

Conclusions

The direct laser fabrication of nanostructures over a range of materials opens new avenues to <u>produce, accelerate and measure</u> charged particle beams at the CERN accelerator complex

Photoemission enhancement via hot electron production in laser-produced nanostructures

- Nanospheres:
  - Enhancement up to 25x
  - Hard to control size and distribution
- LIPSS
  - No enhancement observed in the experiments
- Reducing the nanostructure periodicity and features using DUV femtosecond pulses:
  - Highly heterogeneous nanostructure synthesis
  - Efficient photo-oxidation: Not good for accelerators, but great for coloring metals

Free-electron light sources based on silicon nanophotonics

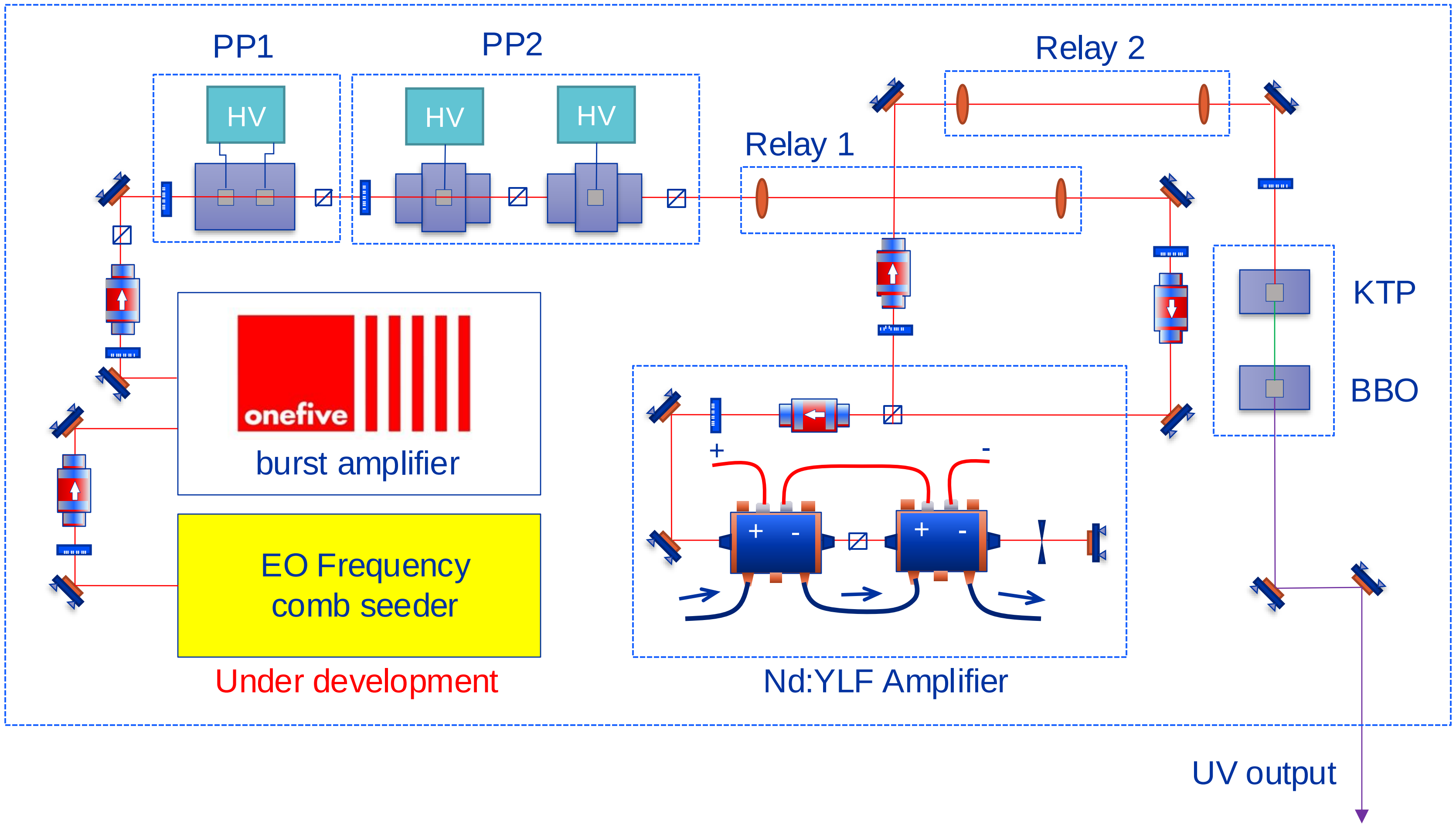
- Record aspect ratio, 100 nm height for periodicity of 250 nm
- Silicon crystalline structure is maintain through the synthesis process
- Applications beyond accelerators include high efficiency photovoltaics, detectors, sensors.

Special thanks to:

NTNU Norwegian University of Science and Technology
Université Jean Monnet Saint-Étienne
Tecnun Universidad de Navarra
CSIC
IO LPG
IOM Leibniz Institute of Surface Engineering
ceit Member of Basque Research & Technology Alliance
CIC nanoGUNE Member of Basque Research & Technology Alliance

home.cern

Electro-optic frequency comb development status



Electro-optic frequency comb development status