

FCC week
21st May 2025

FCC-ee top-up operation: photocathodes and laser systems



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In collaboration with PSI:

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PSI



Outline

Photo-injector main parameters

- Baseline and current specification

Photocathodes

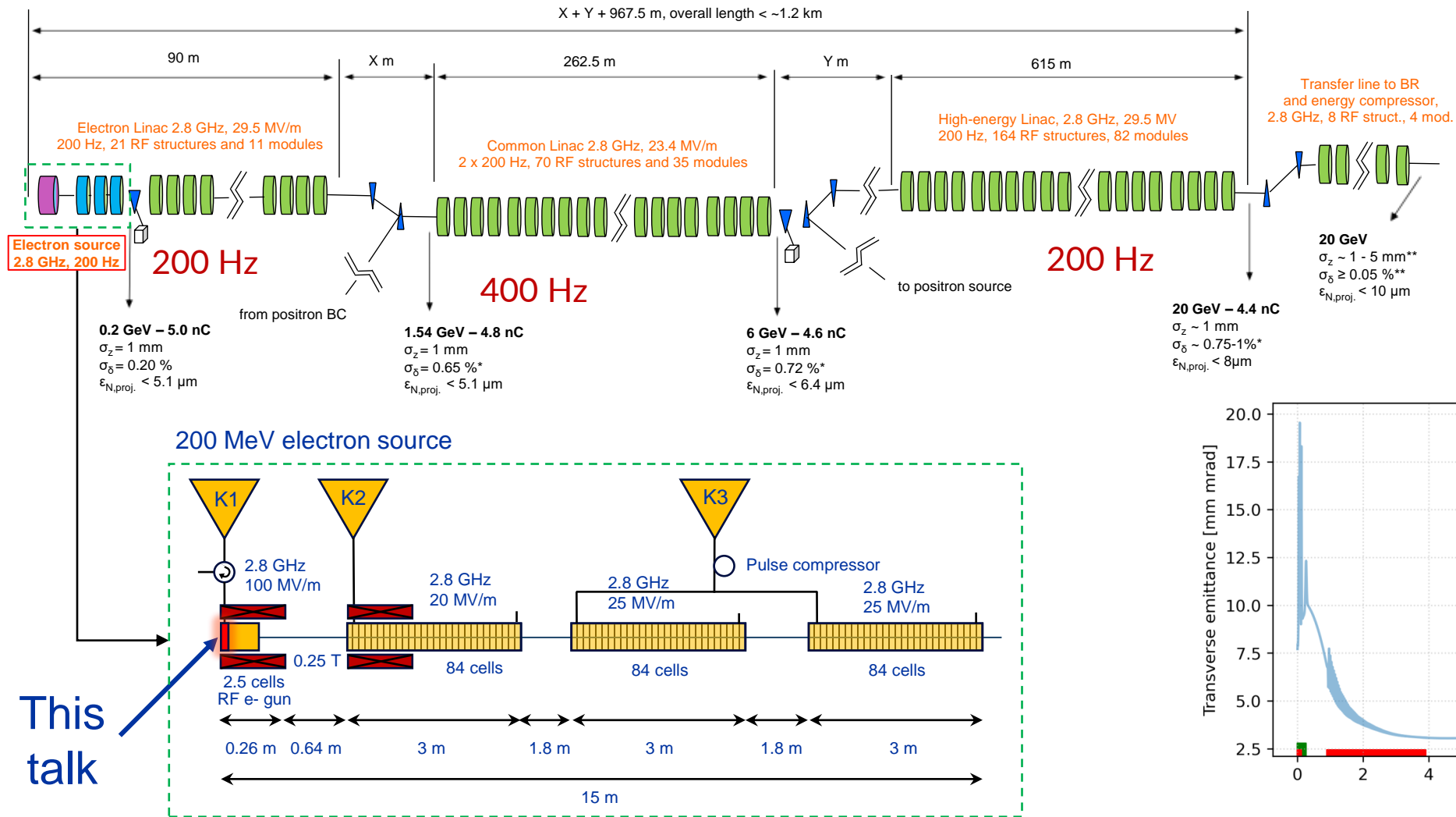
- Overview of photocathode performance, capabilities and limitations...
- Charge production tests at CERN

Laser and optical systems

- Main laser architectures
- UV pulse spatial shaping

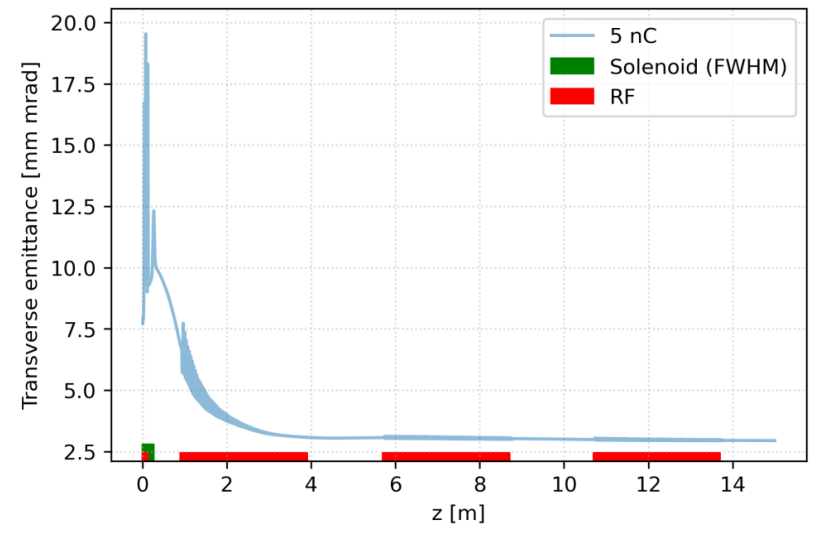
Conclusions

Baseline layout electron linac



- Detailed baseline design studied
- Top-up mode studied: Robust solution to preserve shot-by-shot emittance for different bunch charges
- **Next steps:** Design and test hardware to demonstrate top up mode charge variation

This talk



Courtesy of S. Doebert and Z. Vostřel



Bunch structure and charge requirements

Baseline operational parameters for electron production

Bunch parameter	Specification
Bunch charge	5 – 7 nC
Bunch duration	~3 ps (rms)
Bunch spacing	25 ns
Bunch number (Nb)	2 – 4 (depending on operating mode)
Repetition rate	Up to 200 Hz
Transverse emittance	~ 7 mm mrad (at gun level)
Transverse emittance	~ 4 mm mrad (at 200 MeV)
Energy spread	390 keV (0.2%)

“Worst case scenario”

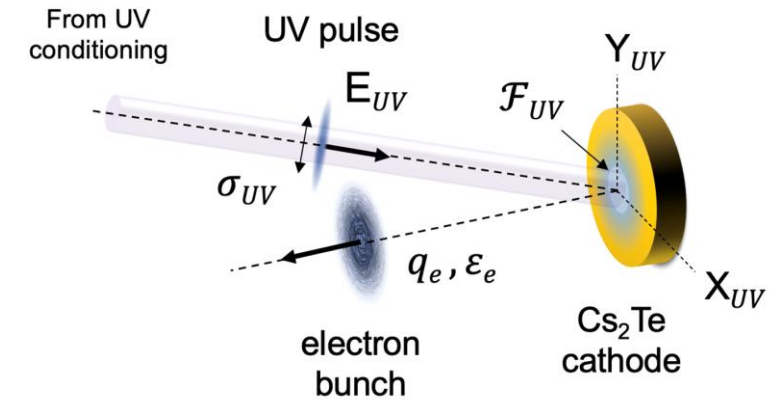
Top-up specific

Bunch parameter	Specification
Top-up range	0 – 7 nC
Accuracy	TBD *
Response time	< 50 ms
Transverse profile	On-demand shaping capability
Transverse emittance	~ 7 mm mrad (at gun level)

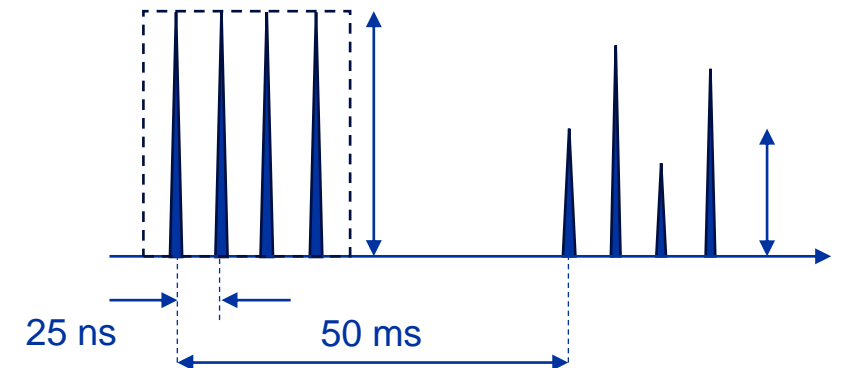
* Fast laser power attenuator

Requirements

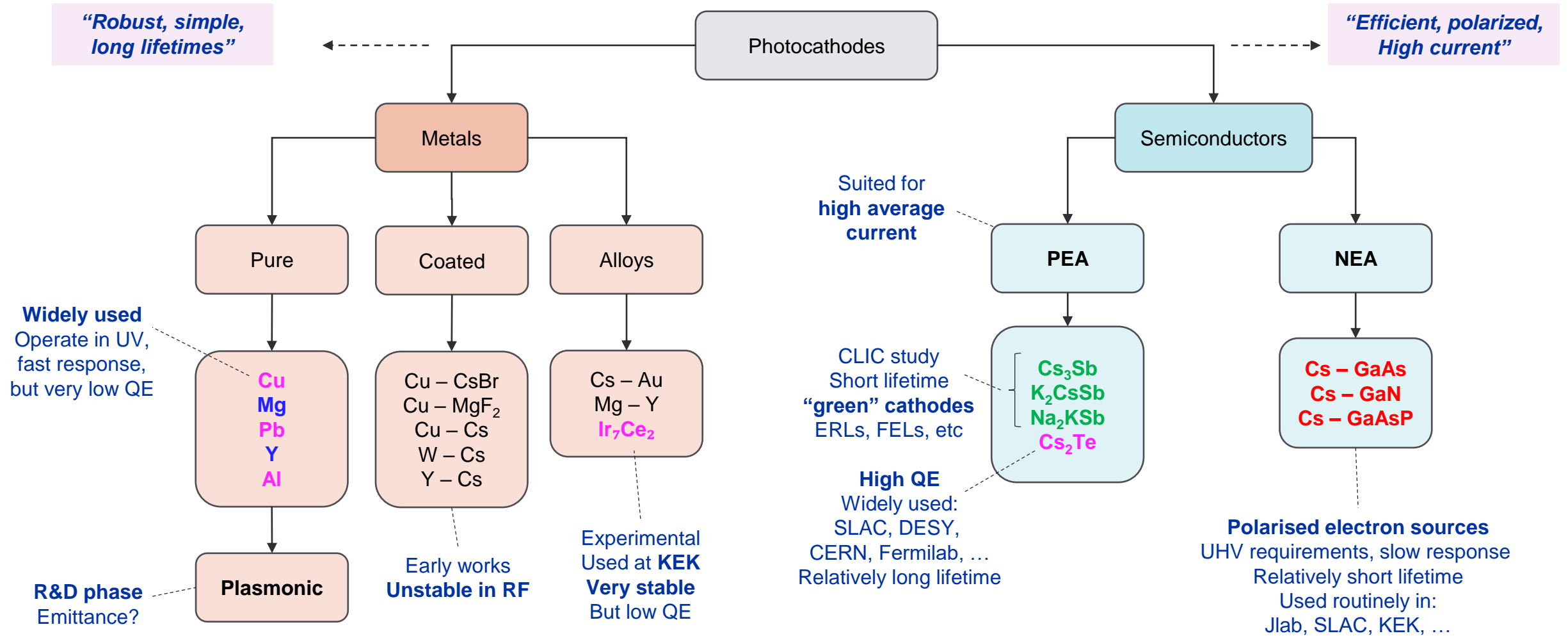
1. Tailoring of transverse beam profile



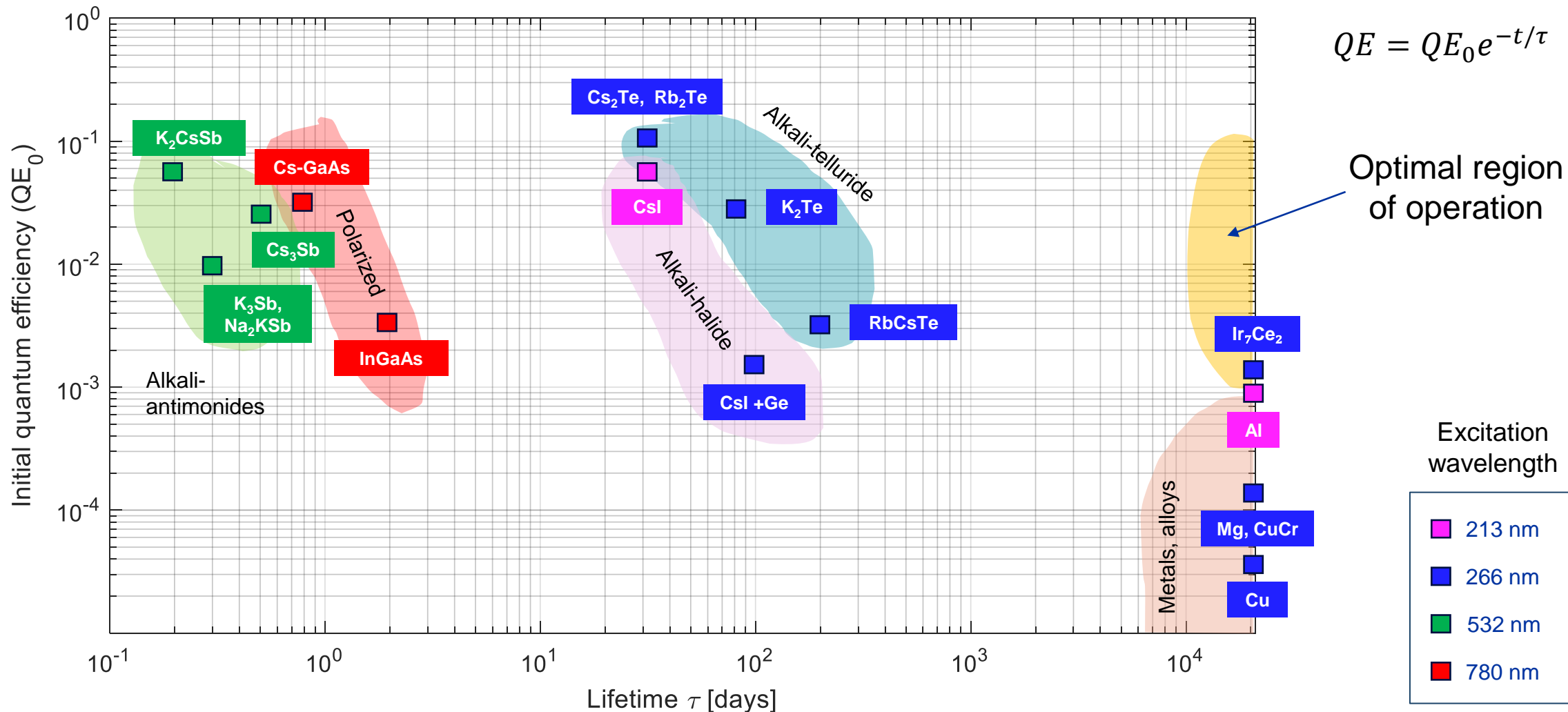
2. Fast and precise amplitude modulation scheme



Photocathode types (non-exhaustive)



Photocathode types (non-exhaustive)

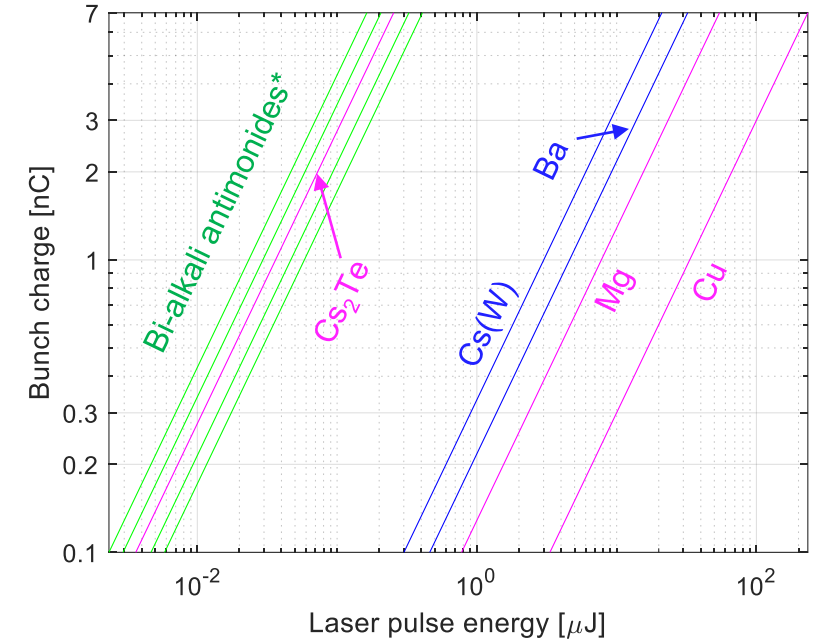


Laser requirements for Cs_2Te and Cu photocathodes

Minimum laser requirements

Parameter	QE 1% (Cs_2Te)	QE $\sim 10^{-4}$ (Cu)
Pulse energy	> 3 μJ	> 200 μJ (> 1 mJ)
Pulse duration (tunable)	1 – 5 ps rms	0.1 – 5 ps rms
Bunch rep. rate	n x 40 MHz	200 Hz + split & delay
Burst rep. rate	200 Hz	200 Hz
Transverse profile	TEM ₀₀ ($M^2 < 1.3$)	TEM ₀₀ ($M^2 < 1.3$)
Shot-to-shot stability	< 1% rms	< 1% rms
Wavelength	257 – 266 nm	257 – 266 nm
Architecture	<ul style="list-style-type: none"> Burst mode laser High energy laser with split and delay 	<ul style="list-style-type: none"> Multiple lasers Split and delay system

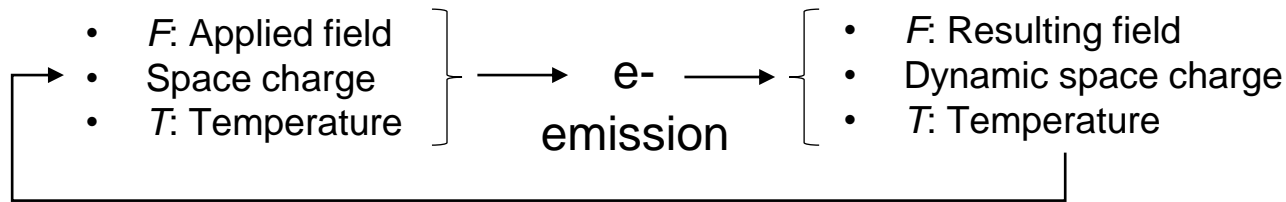
Required laser pulse energy on cathode (neglecting saturation effects)



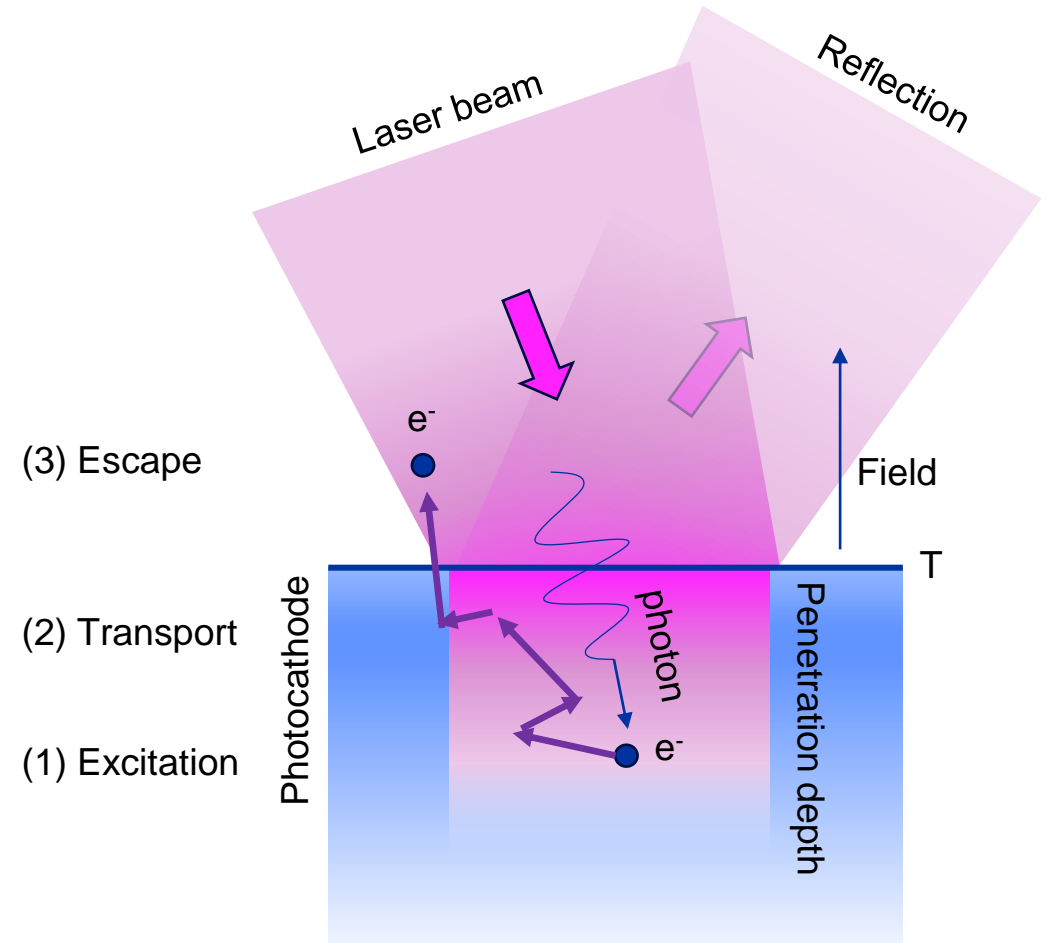
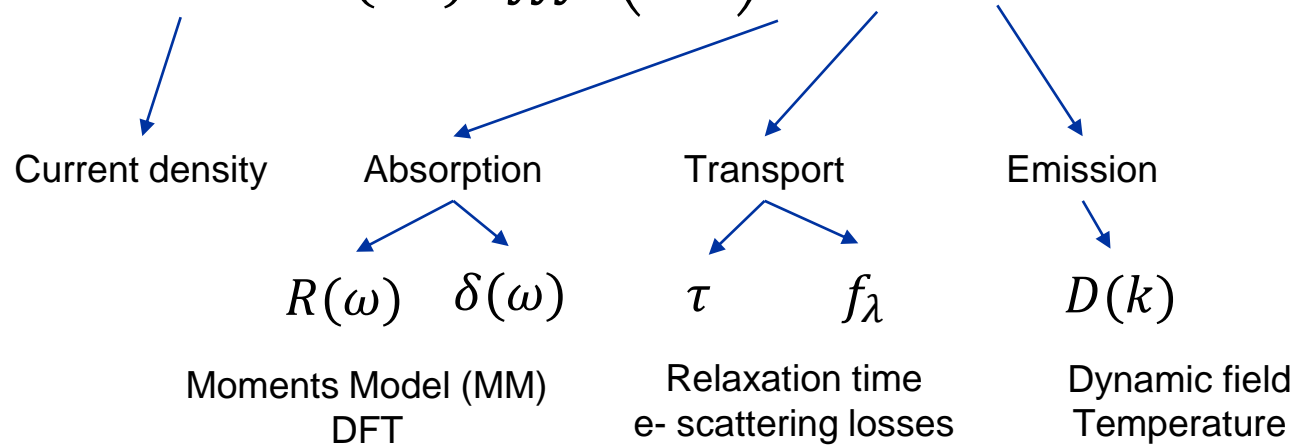
* While bi-alkali antimonide photocathodes have high QE and operate with green excitation wavelength, their development and usage in photoinjectors is still under study

From laser transverse profile to electron bunch distribution

“Everything affects photoemission”

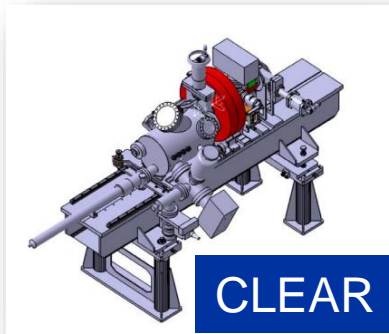


$$J(\hbar\omega) = \frac{2}{(2\pi)^3} \iiint \left(\frac{\hbar k_z}{m} \right) A \times T \times E dk_z dk_{\perp}$$

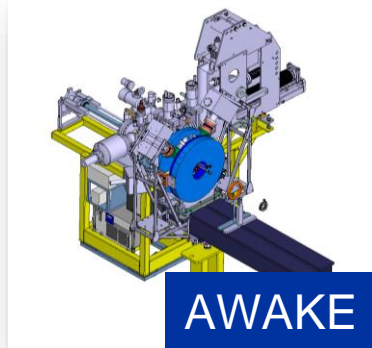


Photoemission models need to be **integrated** into existing beam dynamics simulators

Testing in electron sources at CERN



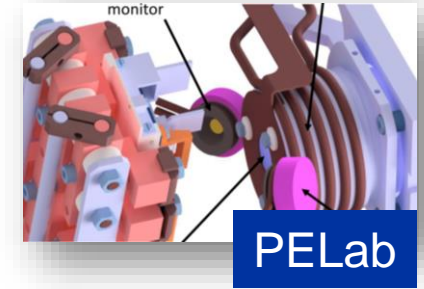
CLEAR



AWAKE



CTF2



PELab

Photocathode technology

Cs₂Te

In-situ

Cs₂Te / Cs₃Sb

Load-lock

Cu

Cs₂Te
Cs₃Sb
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

5 nC
Single bunch

800 pC
Single bunch

10s nC
Single bunch

Laser driver

Nd:YLF
1 uJ, 4.8 ps

Ti:Sapphire
2 uJ, 1.2 ps

Yb:KGW (Pharos)
400 uJ, 200 fs

Nd:YAG
7 mJ, 8 ns

Use

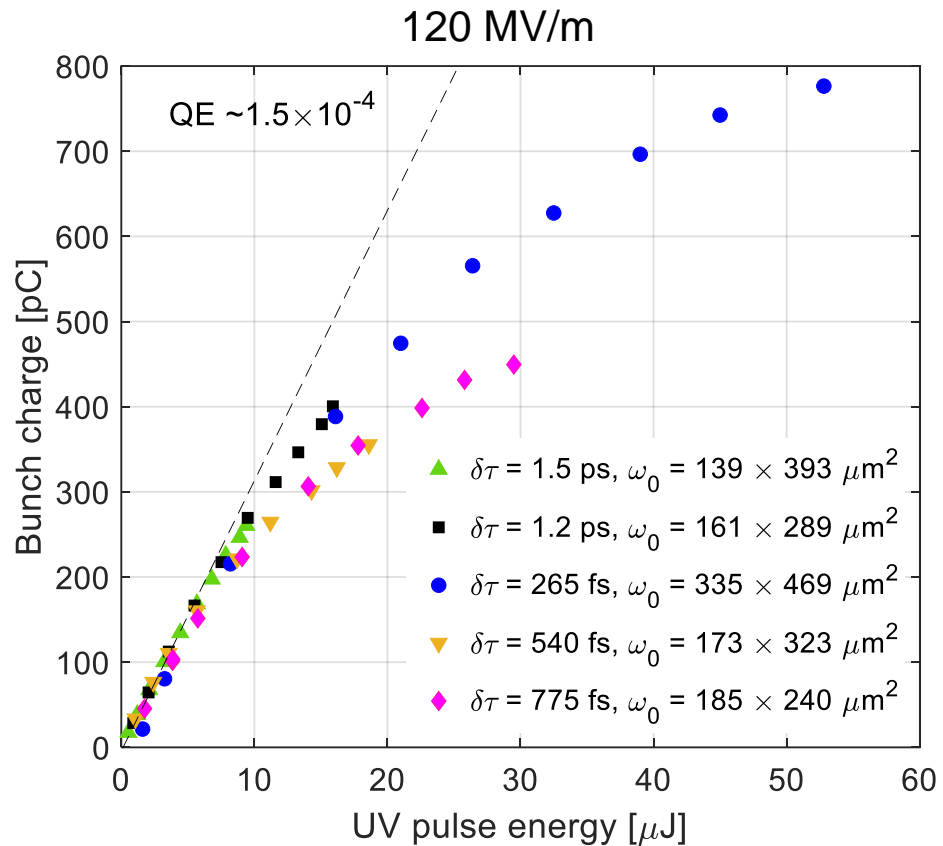
User beamtimes
CLEAR

Witness, SM
AWAKE run 1-2b

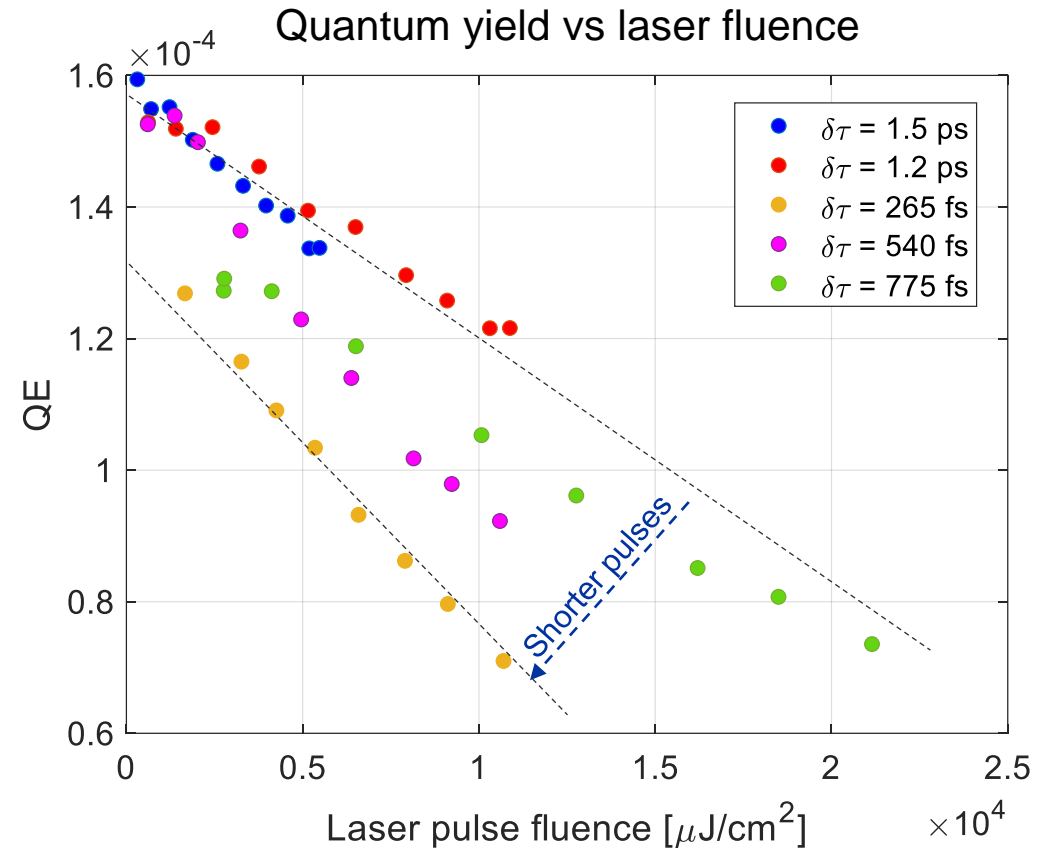
Witness,
AWAKE run 2c

AWAKE production

Charge production tests at CTF2 – copper photocathode



Electron bunch production tests for a range of UV pulse energies, duration ($\delta\tau$ at FWHM), and spot sizes (ω_0 , in both axes, at $1/e^2$).

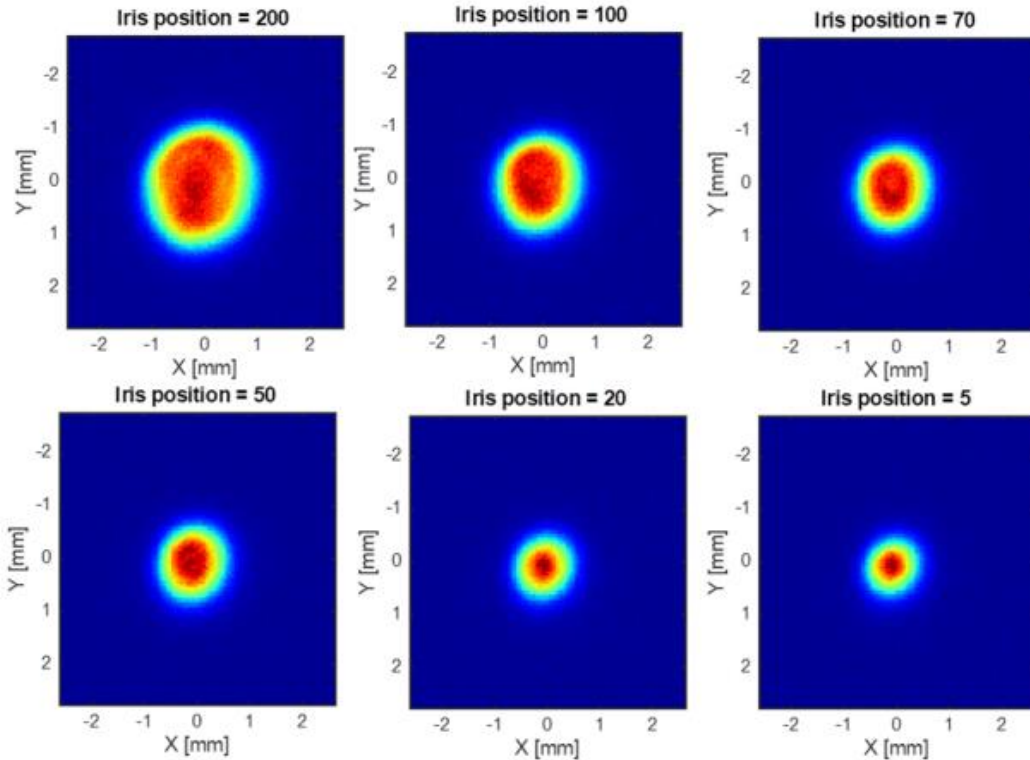


The total produced charge depends on the intensity of the incoming UV beam and the produced charge density

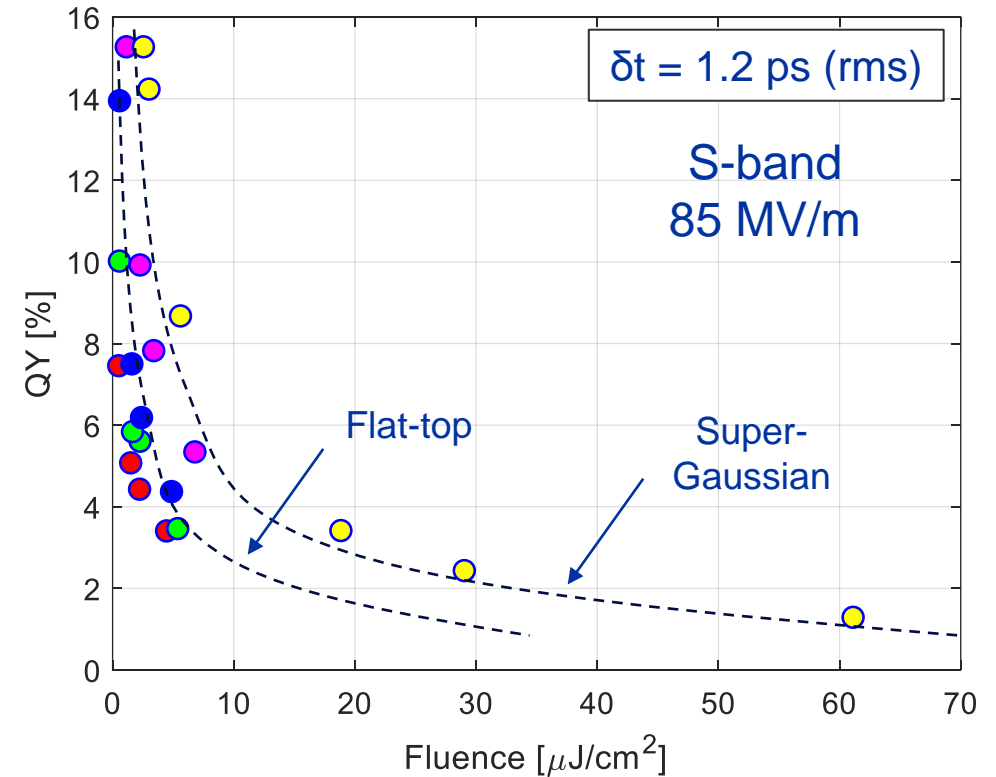
!! Damage threshold copper $\sim 100 \text{ mJ}/\text{cm}^2$

Charge production tests at AWAKE – Cs_2Te photocathode

Quasi-flat-top distribution achieved using a motorized iris and ‘strictly’ relay imaging it to the photocathode



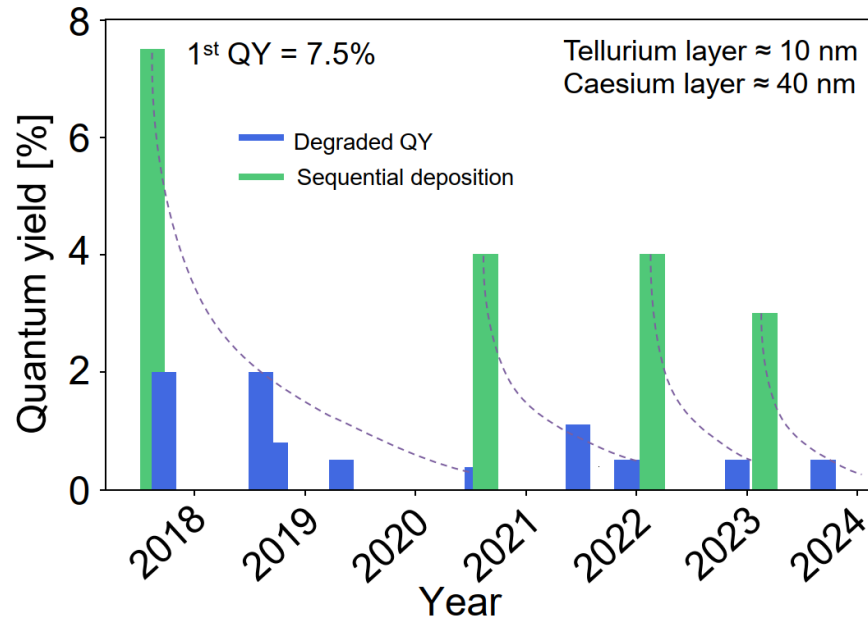
Fresh photocathode:
Up to 5 nC/bunch, 1-2 mm mrad (300 pC)



Reduction in QE is of an order of magnitude when the laser fluence is above $10 \mu\text{J}/\text{cm}^2$

Charge production tests at CLEAR – sequentially deposited Cs_2Te

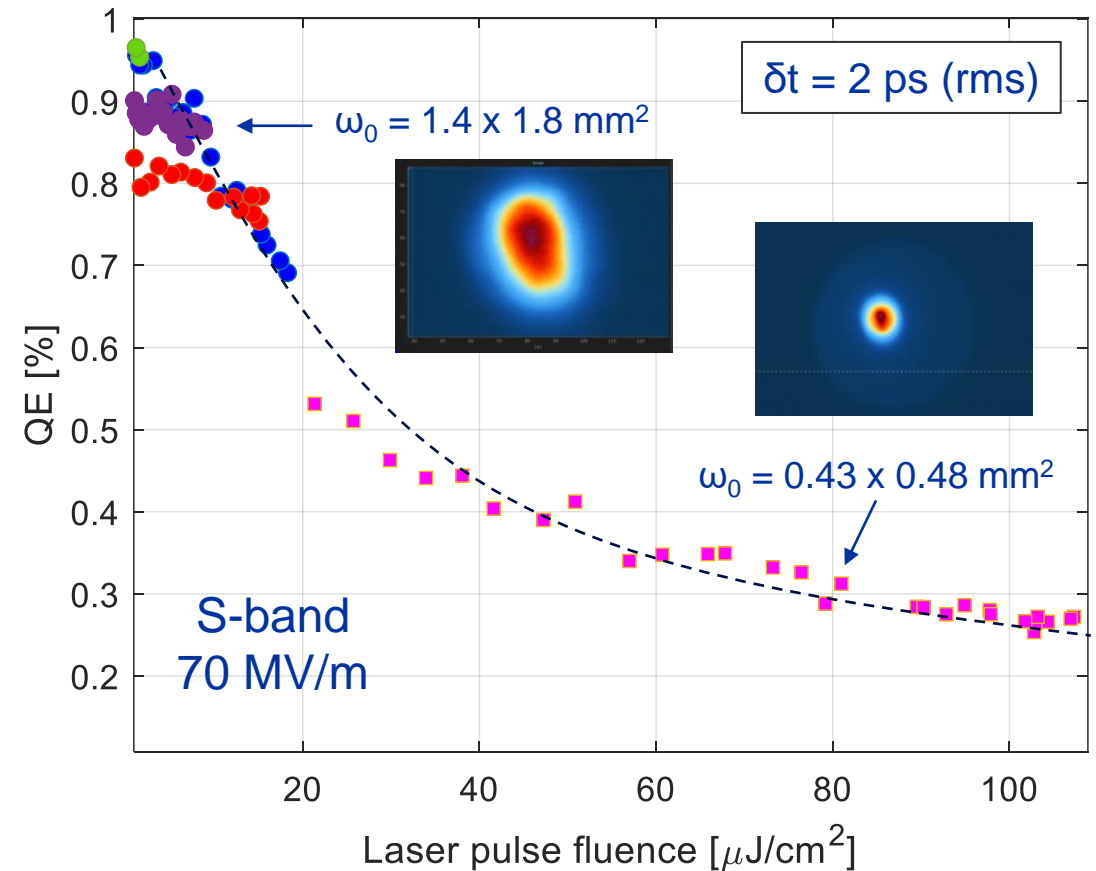
CLEAR – in-situ photocathode fabrication
 Cs_2Te photocathode lifetime ~ 1 year



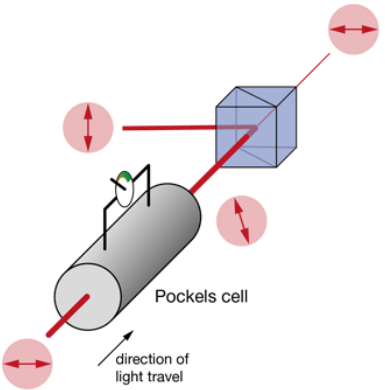
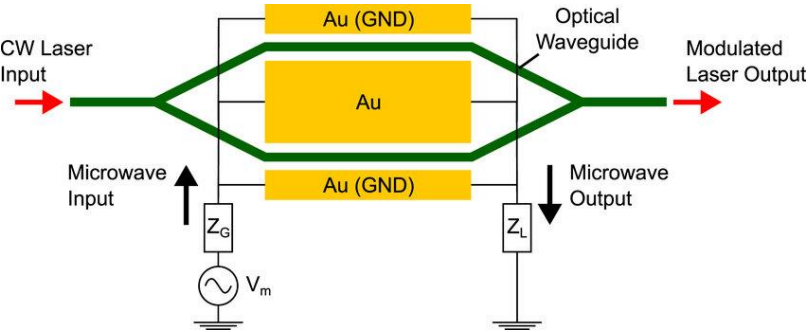
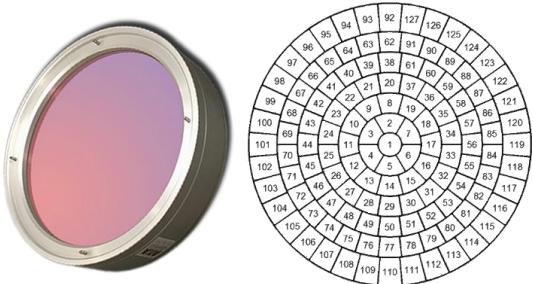
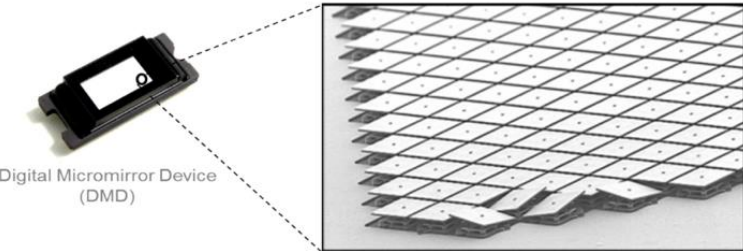
Up to 7 nC/bunch, 20 - 30 mm mrad (1 nC/bunch)

Reduction in QE of a factor of 3 when the laser fluence is above $40 \mu\text{J}/\text{cm}^2$

Variable spot size (Gaussian-like distribution) achieved using a motorized telescope + variable attenuator

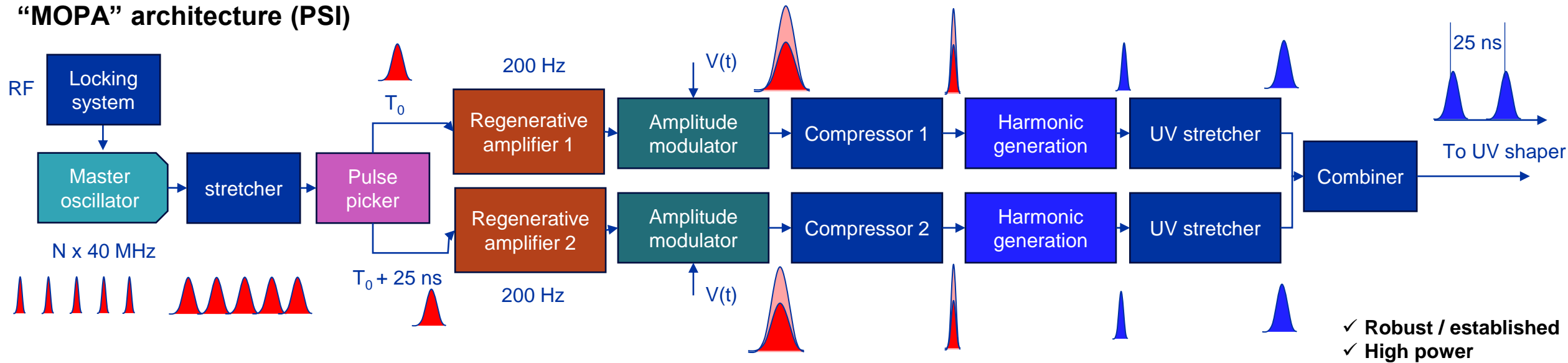


UV laser beam shaping techniques for FCC-ee top-up

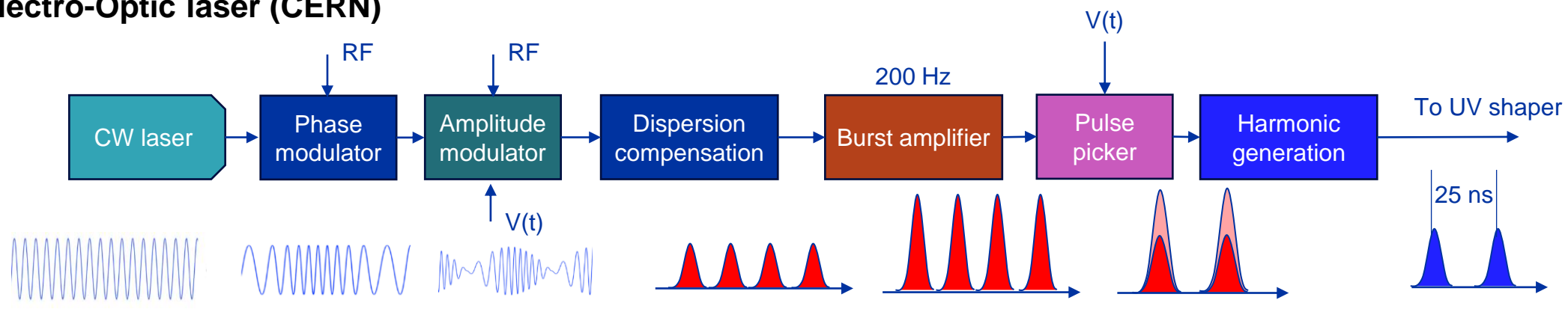
	PSI	CERN
<p>On-demand amplitude modulation</p>	<p style="text-align: center;">PSI</p> <p style="text-align: center;">Pockels cell</p> 	<p style="text-align: center;">CERN</p> <p style="text-align: center;">Electro-Optic front-end laser (MZM)</p> 
<p>Transverse profile shaping devices</p>	<p style="text-align: center;">Deformable mirror</p> 	<p style="text-align: center;">Digital micromirror device</p>  <p style="text-align: center;">Array of micromirrors</p>

Possible laser architectures for FCC-ee top-up scheme

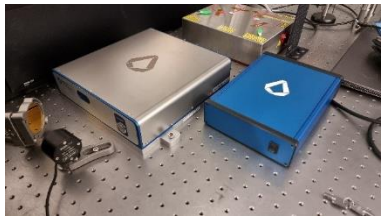
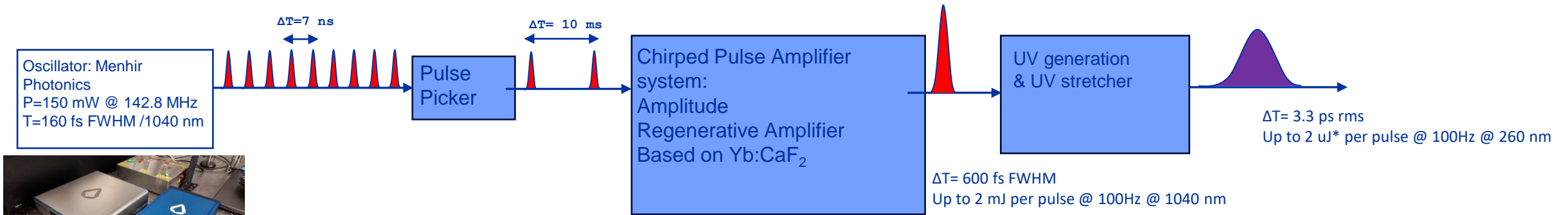
“MOPA” architecture (PSI)



Electro-Optic laser (CERN)

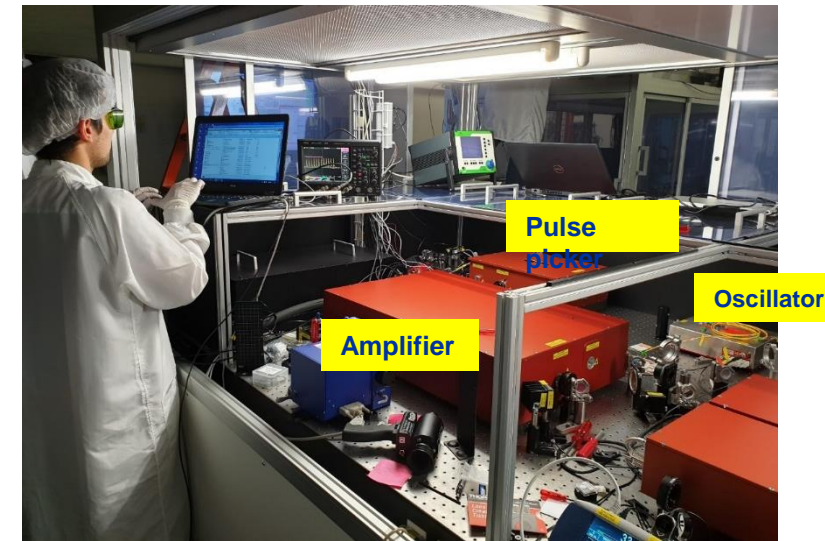


Possible architecture photocathode laser at PSI



* Assuming a CsTe cathode with QE=1%, 1.5 uJ would be enough to generate 5 nC

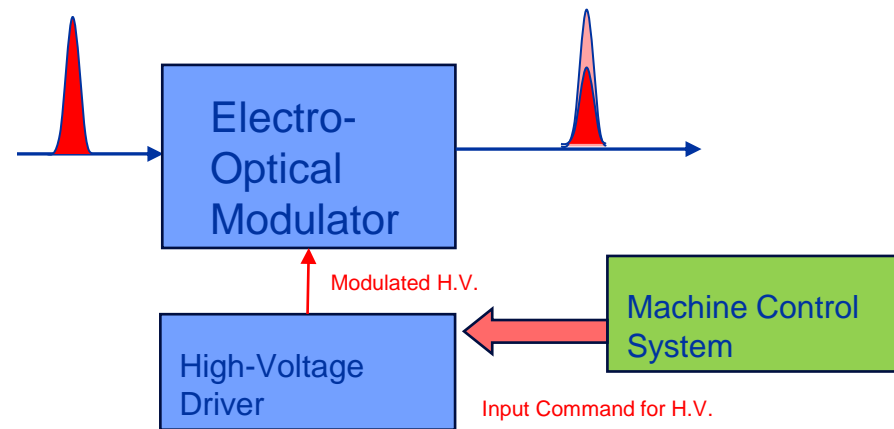
- Innovative and performant technology: in operation at SwissFEL since 2015
- Ultra-low timing jitter of the synchronized laser: <20 fs rms over 10Hz-10MHz
- Multi-mJ pulse energy in the IR
- Uneven pulse energy stability ~0.05% rms @ 1040 nm and ~0.03% rms @ 260 nm
- Compact = more passive stability
- Directly diode pumped



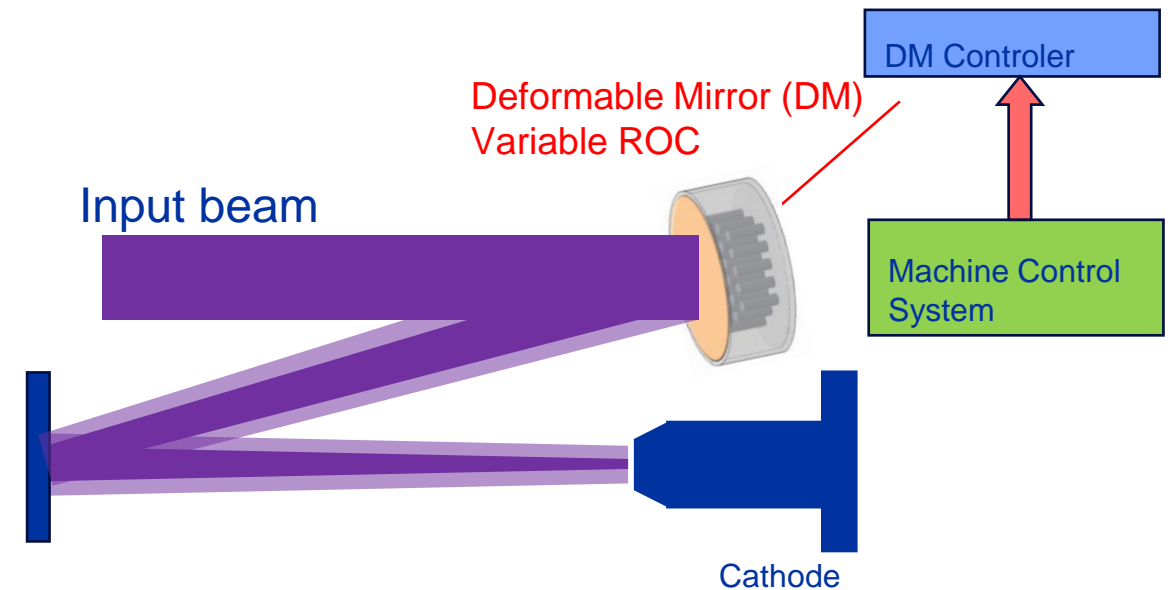
Shot-to-shot adjustment capabilities at PSI

Requirements: generate 5 nC electron bunch at 100Hz with the shot-to-shot capability to:

1. Modulate the electron bunch charge from 0-5 nC

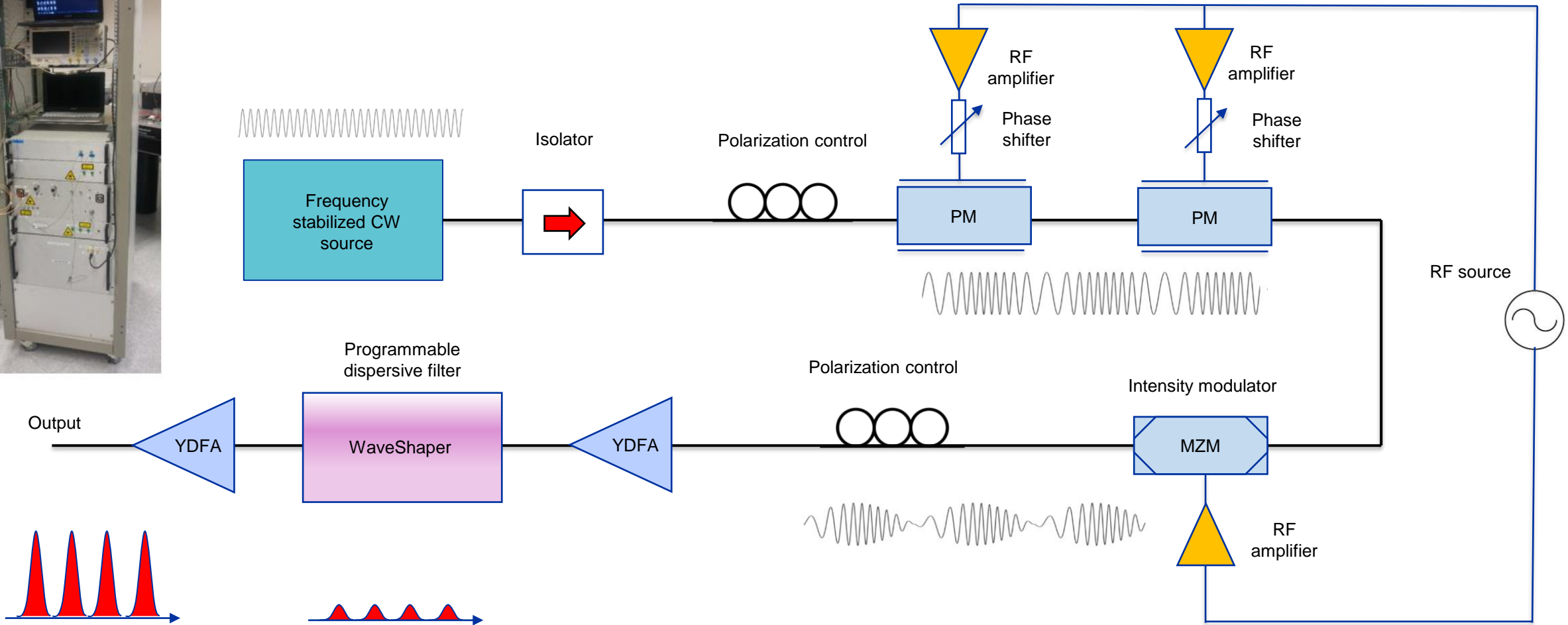
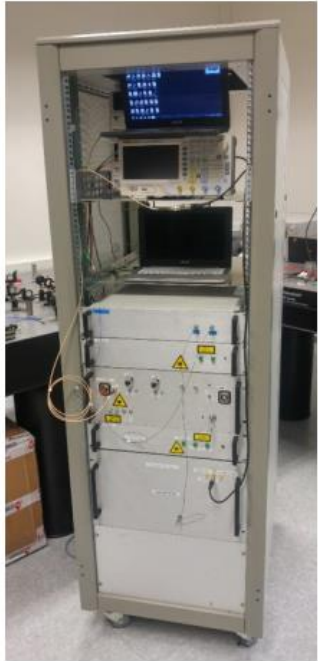


2. Adjust the laser beam size on the cathode

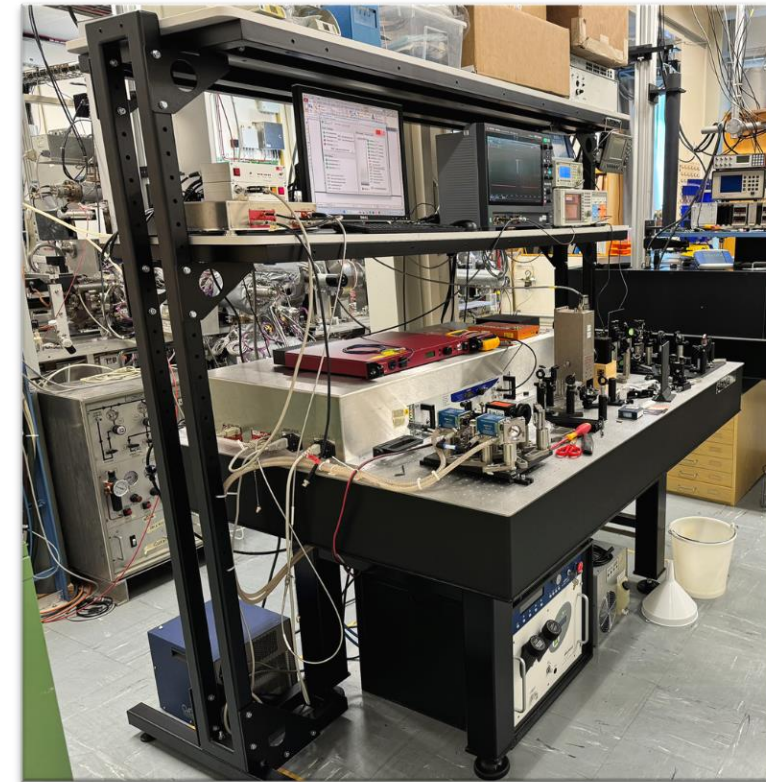
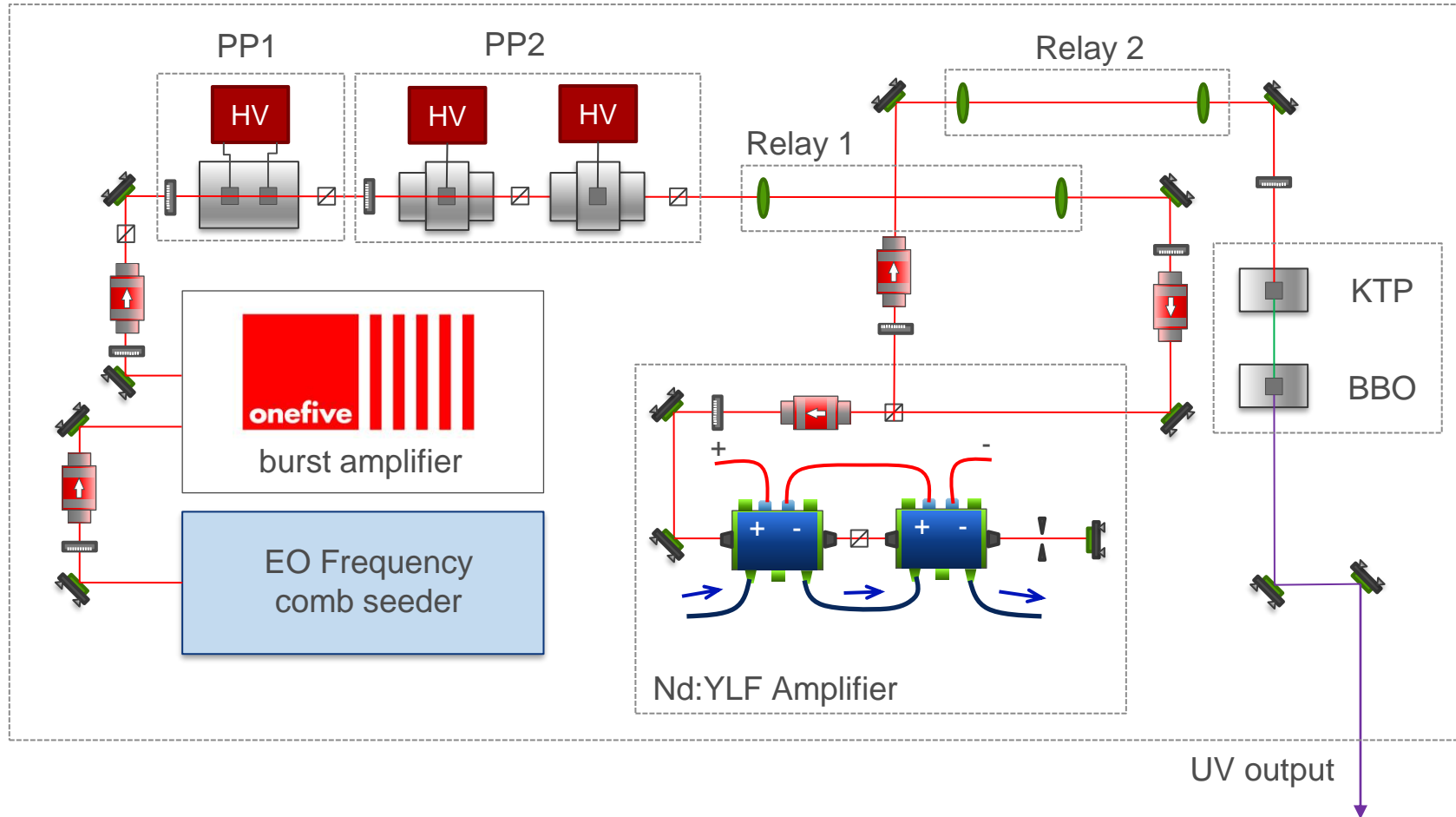


➤ Well established and reliable technologies

Electro-Optic front-end laser modulation scheme at CERN

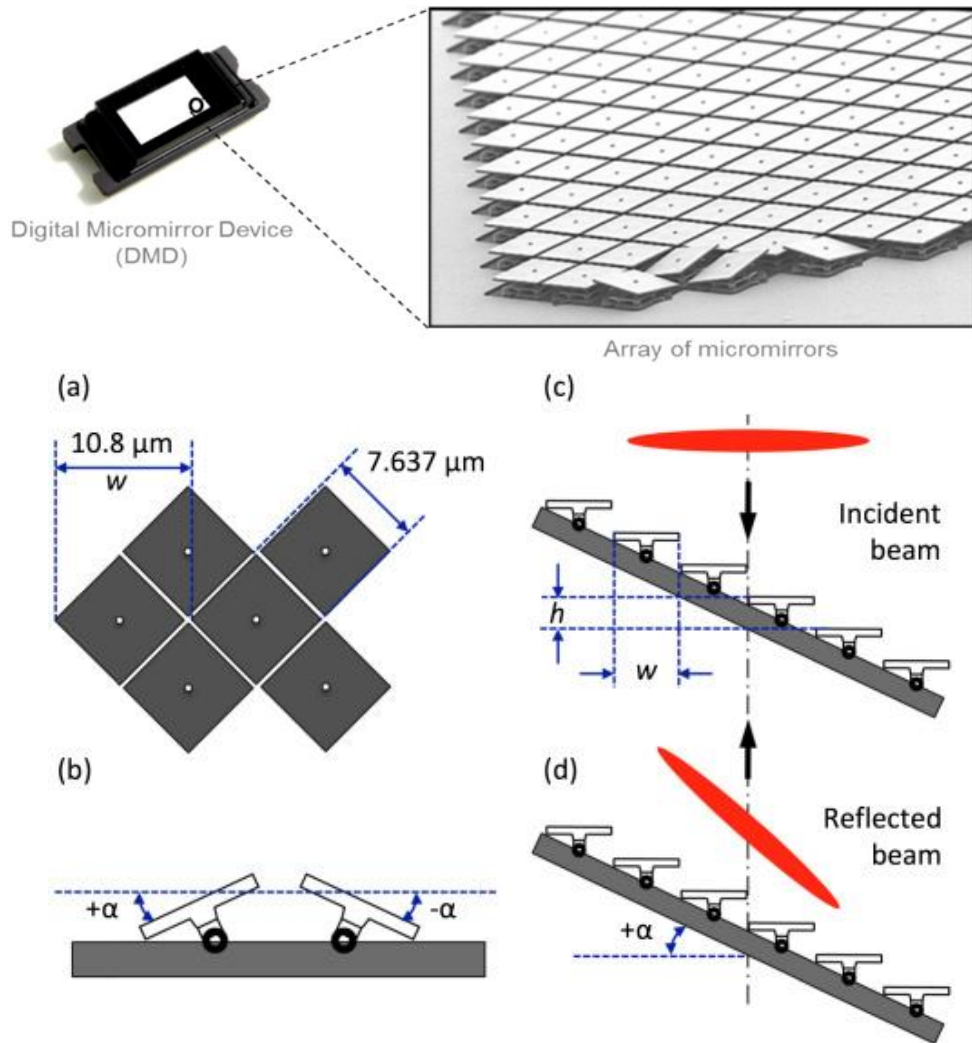


Electro-optic burst mode amplifier development at CERN



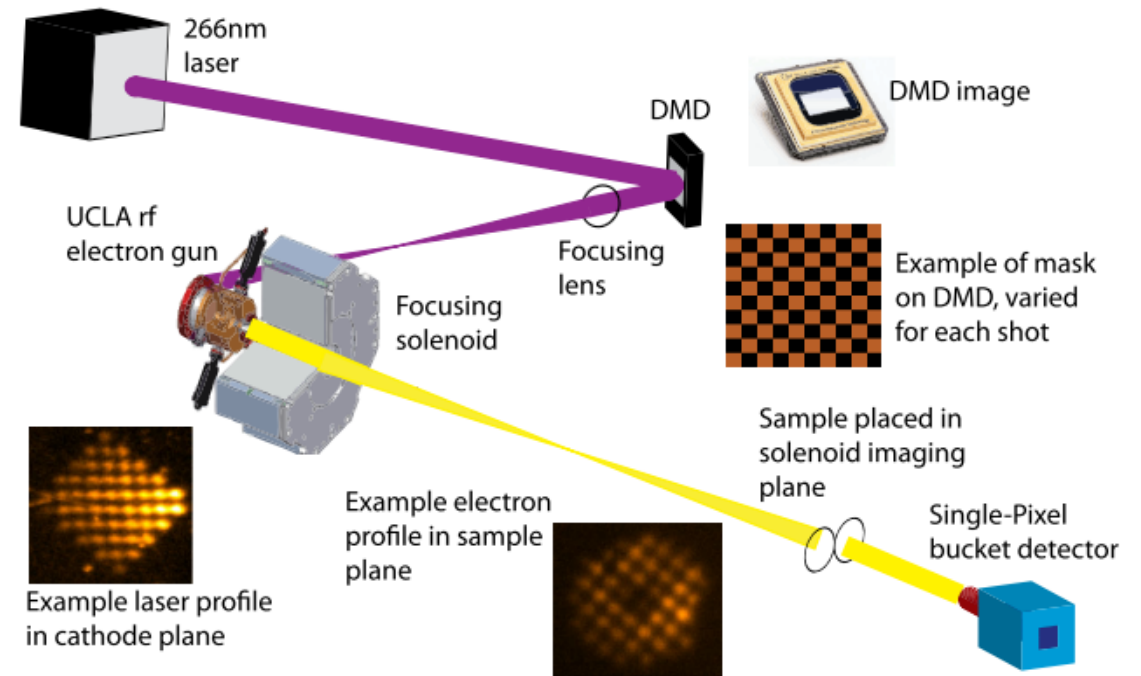
Will serve as CLEAR photoinjector laser upgrade when completed

Digital micromirror device for UV beam shaping



Demonstrations in RF guns exist (UCLA, SLAC)

- **Low damage threshold**
- **Pulse front-tilt management necessary**



Phys. Rev. Lett. **121**, 114801 (2018)

DOI: <https://doi.org/10.1103/PhysRevLett.121.114801>

Conclusions

Photocathodes

- Choice is influenced by **quantum efficiency, lifetime**, vacuum requirements, fabrication method, and properties of the electron beam to be produced (for example, **spin polarization**).
- For tests, **Cs₂Te** and **Cu** are currently available, in the meantime we need to consider the production of alloy photocathodes (**Ir₇Ce₂**) with “infinite” lifetime and **Cs-GaAs** options for polarized photoinjector.

Laser and optical systems

- For producing the temporal bunch structure, the options currently considered for testing are:
 - **MOPA architecture** with multiple laser lines, then recombine them at the photocathode level (well established). Tests will be carried out at **PSI**.
 - **Electro-Optic front-end** in combination with burst amplifiers (experimental). Tests will be carried out at **CLEAR**.
- In terms of the UV shaping technique, two approaches will be explored:
 - **Deformable mirror**, which allows for high pulse energy on photocathode (suitable for low QE photocathodes)
 - **Digital Micro-mirror Device (DMD)**, which allows fast masking of the UV beam profile (*higher resolution* but more lossy, works better with high QE photocathodes)