CLEAR photoinjector

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On behalf of SY-STI-LP

Agenda

- CLEAR:
  - Upgrades / consolidation of laser system
  - Performance
  - Spares
  - Next steps:
    - Electro-optic frequency comb laser development
    - Photoinjector with advanced spatio-temporal capabilities compatible with FCC-ee
- CTF2:
  - Commissioning of laser system and electron beam
  - ICS experiments

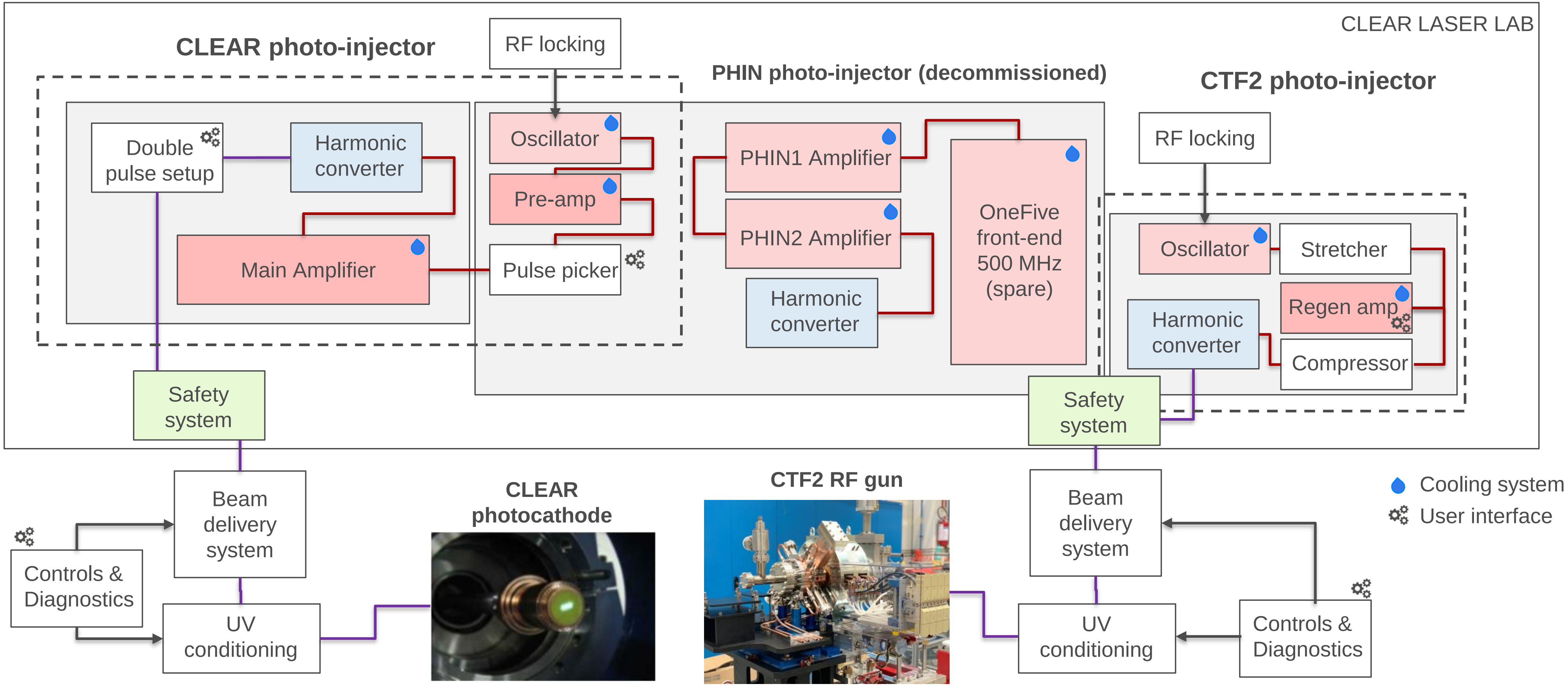
Recap: plans and needs for the period 2022-2025

Activity	2022				2023				2024				2025			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
CLEAR																
Laser support / Troubleshooting																
Maintenance of cooling system																
DSO tests, laser safety systems																
Cathode performance study																
Photoemission lab																
CLEAR CsTe cathodes rejuvenation and conditioning																
CsTe cathode production and new load-lock system for CTF2																
Testing of CsTe cathodes for CTF2																
CTF2 photoinjector																
Installation of UV laser																
RF locking system tests																
Beam transport system construction																
UV conditioning table installation																
Diagnostics implementation and commissioining																
UV beam delivery to cathode and charge production tests																
Operational support and troubleshooting																
(Dismantling for transport to AWAKE)																

New CTF2 photo-injector laser installed at CLEAR

- CLEAR photo-injector laser points of failure:
  - Ageing oscillator: potential failure or compromised performance – could be replaced by OneFive system but operating at 500 MHz.
  - Laser sub-systems often fail and require replacements and spares: Chillers, pulse-picker power supplies, laser diodes, laser power supplies, beamline optical elements, and motors.

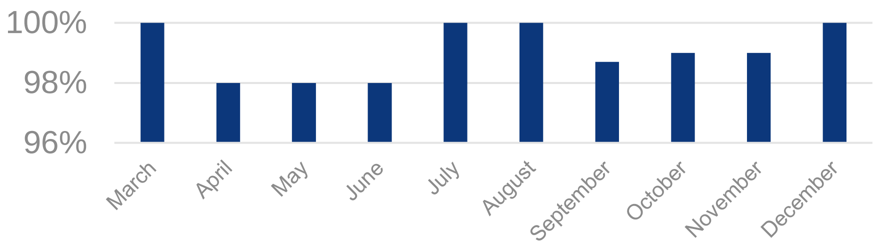
Schematic layout of CLEAR injector systems



CLEAR operation during 2023

	March	April	May	June	July	August	September	October	November	December
Beamtimes	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
	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. Laser oscillator procured, collaboration with U. Bordeaux launched. Expected commissioning Q4 2024.



https://pkorysko.web.cern.ch/CLEAR/Table/CLEAR_experiments.html

CLEAR laser system consolidation

Laser oscillator → Pre-amplifier → Pulse picker → Power amplifier → Harmonic conversion → Transport → Conditioning system → e- gun

Laser oscillator

- ✓ New SESAM mirror (2022)
- ✓ Pump diode replacement (2023)
- ✓ Steering optics with low thermal expansion (2021)
- ✓ RF locking jitter issues (2023)
- ✓ Amplitude modulation issues (2018-2023)

No Spares

Pre-amplifier

- ✓ Replacement of pumping diode stacks (2019, 2021, 2023)
- ✓ Cylindrical lenses replacement (2021, 2023)
- ✓ Refurbishment of used diode stacks (2022)
- ✓ Cooling system work (every year)

No Spares

Pulse picker

- ✓ Repair of HV power supplies (2019, 2020, 2021, 2022, 2023, 2024)
- ✓ New upgraded design for HV PS in (2022)
- ✓ Commissioning of supercharge mode (2020)
- ✓ Timing jitter minimization (2019)
- ✓ Impedance matching for ultra-flat-trains (2020)

Power amplifier

- ✓ Many leaks repaired in diode stack cooling system (every year)
- ✓ Pumping chamber corrosion – replacement (2023, 2024)
- ✓ Spare amplifier designed, procured and commissioned (2021, 2024)
- ✓ Diode stacks repaired; 1 spare produced (2022)

Harmonic conversion

- ✓ New harmonic crystals installed (2019, 2021)
- ✓ High precision oven with remote capability (2020)
- ✓ Fundamental, VIS, and UV monitors (2020)
- ✓ 3 GHz train and double pulse capability (2019)
- ✓ Full motorization of attenuators and polarization (2021)

Transport

- ✓ Nitrogen pressure for relay system (2019)
- ✓ Replacement of windows and relay optics (2020)
- ✓ On-line power meters before and after transport (2023)
- ✓ New shutter motor and power supply (2019, 2022)
- ✓ 16 GHz traces for users (2021)

Conditioning system

- ✓ Stepper motors for beam steering (2018)
- ✓ Variable spot size on cathode (2019)
- ✓ Imaging system repairs (2022)
- ✓ UV imager 4x (2019)
- ✓ Variable aperture (2020) – decommissioned
- ✓ New PLC for controls and diagnostics (2020)

General upgrades/repairs

- ✓ Upgrades of laser control and diagnostics system (2019-2024)
- ✓ Data publishing real-time via CMW (2024)
- ✓ New PLC installed (2021)
- ✓ AC unit repairs (2019, 2022)
- ✓ New ventilation system (2024)
- ✓ Automatic optimization system (2020-2024)
- ✓ 24/7 operation since (2022)

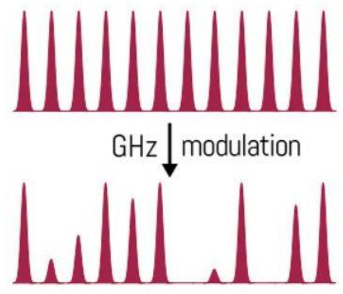
Overall performance

1% RMS stability (5% Pk-Pk)
Up to 7 nC/bunch (>1 nC/bunch)
1 - 150 bunches
0.833 - 10 Hz
1.5 – 3 GHz

Running time

Year	Laser up-time
2021	98.6%
2022	98%
2023	99.6%

Next-gen CLEAR photoinjector laser

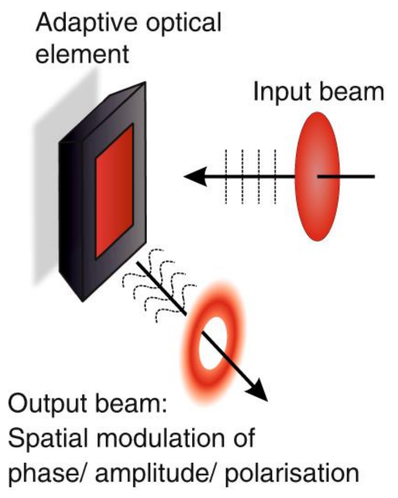


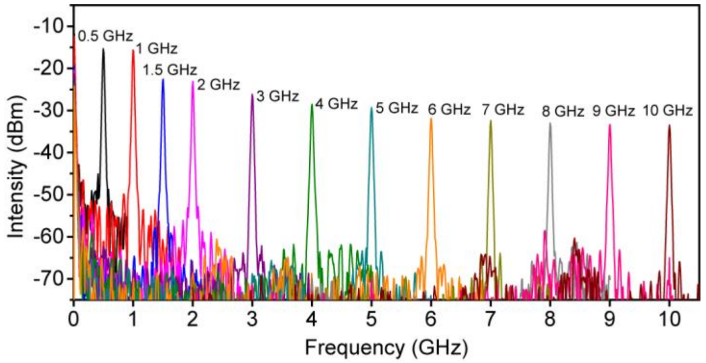
Operating at arbitrary rep. rate MHz up to 12 GHz

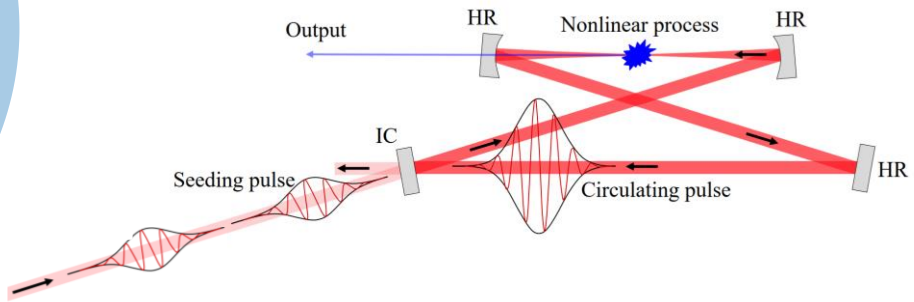
Programmable trains with arbitrary amplitude and beam profile, FCC-ee “top up scheme”

?

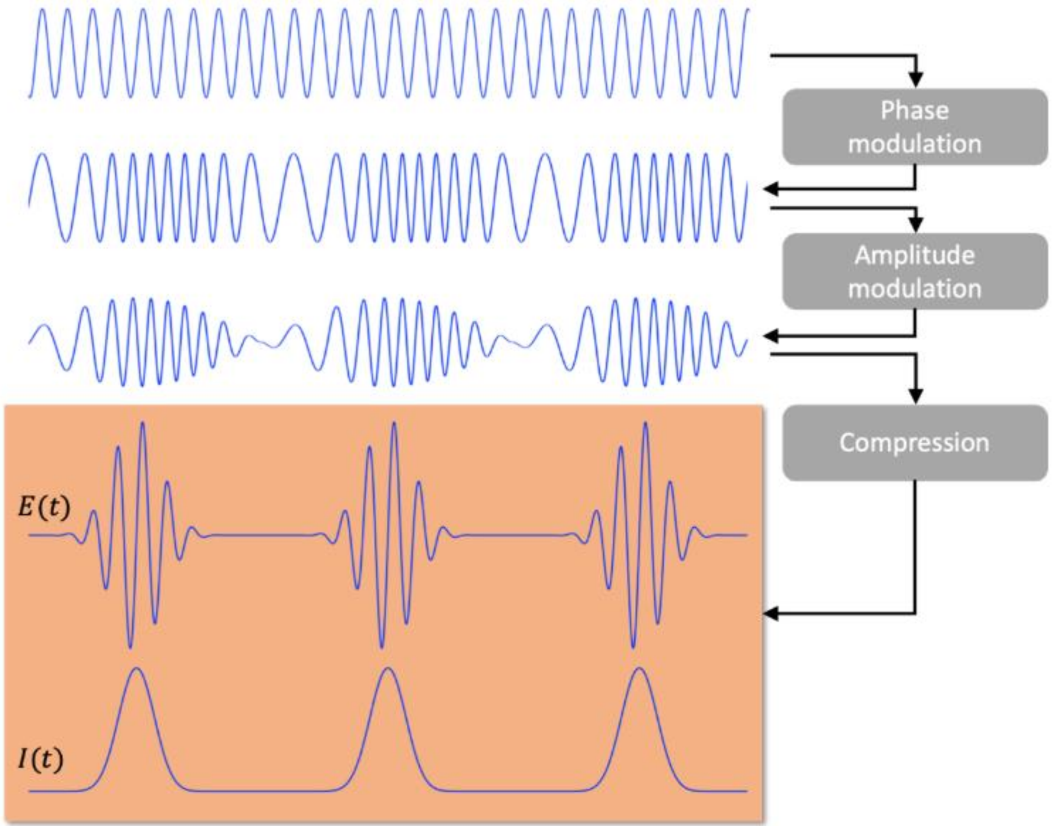
Phase-stability enabling ultra-high intensity laser-electron interaction

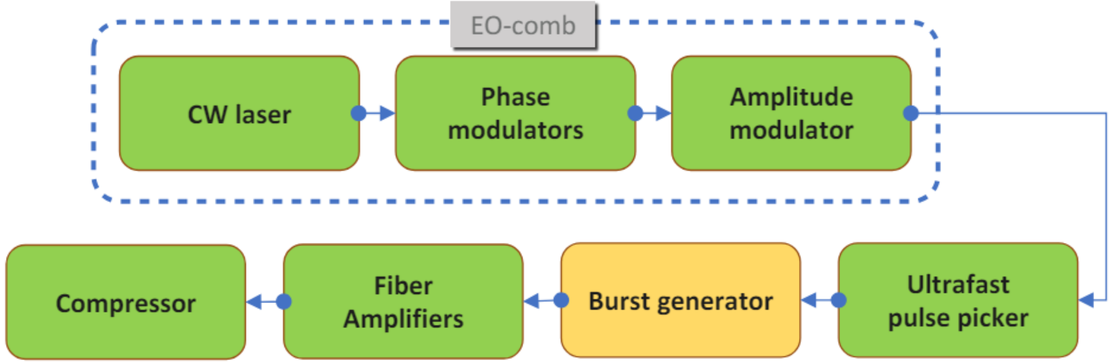


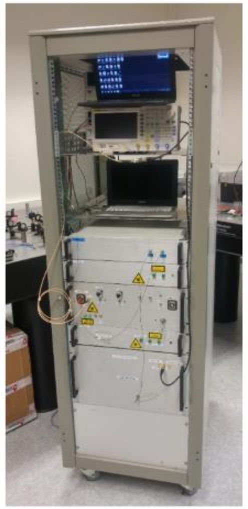




Electro-Optic frequency combs concept







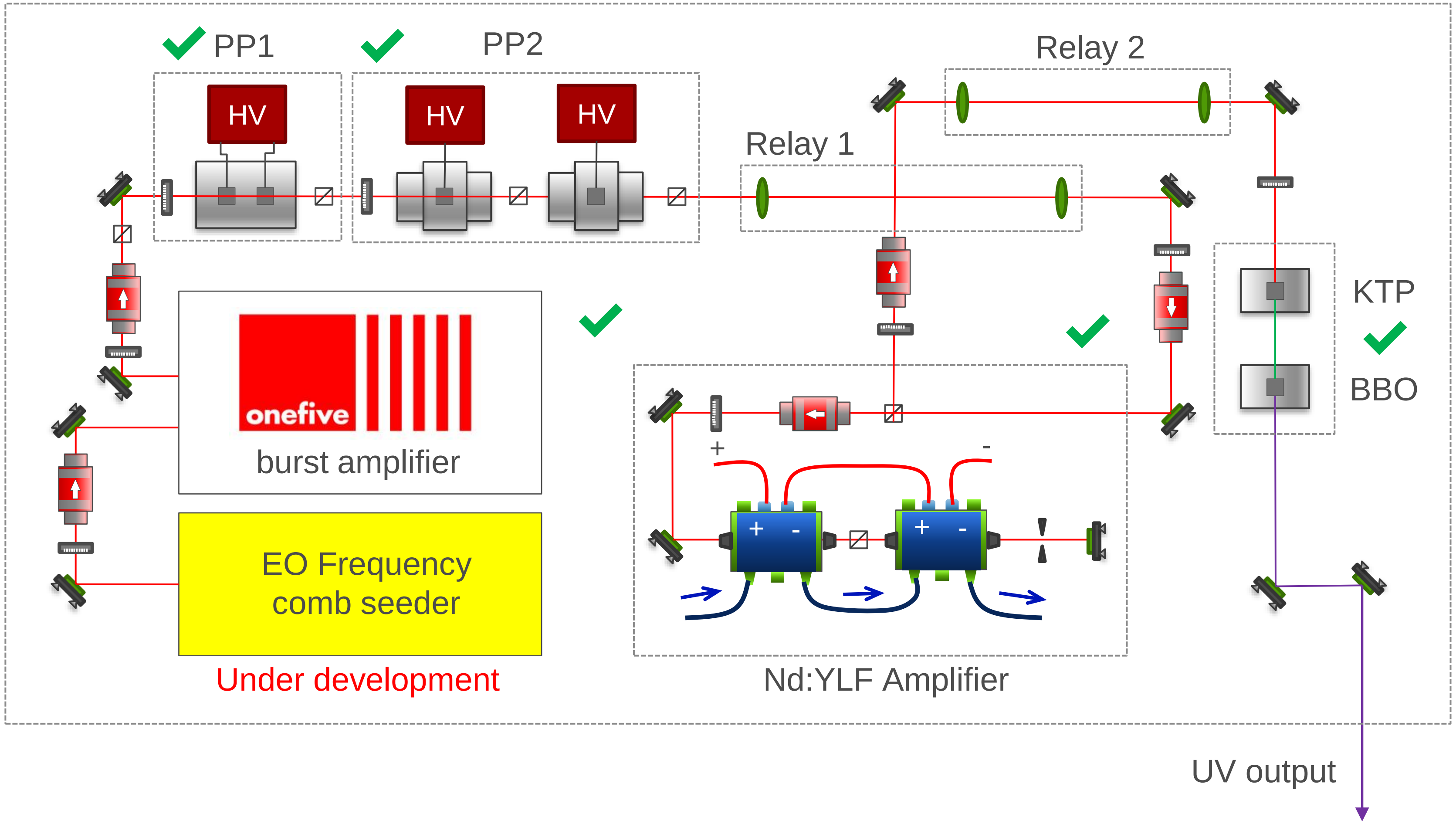
Gigapico Burst Mode:

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

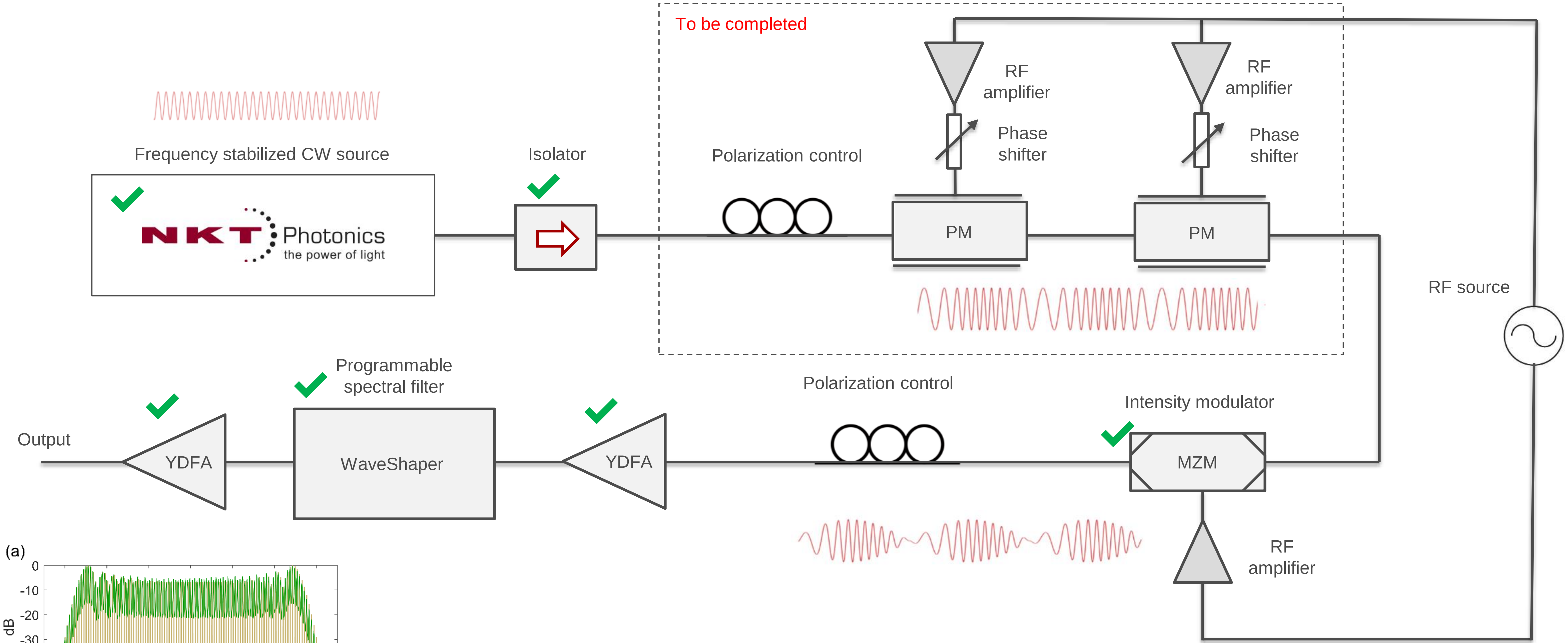
Status EO frequency comb development

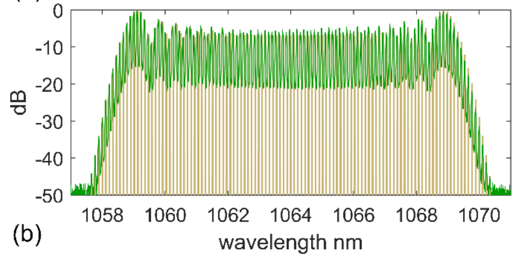
- Prototype under construction in Photoemission lab
- 90% of required items already procured
- Many recycled items from CLIC (300 kCHF in savings):
  - CLIC burst amplifier, 179 kCHF
  - CLEAR booster amplifier, 40 kCHF
  - CLIC harmonic conversion stages, 25 kCHF
  - Amplitude modulators and fiber systems for phase-coding project. (30 kCHF)
  - Optical elements (10 kCHF)
  - Pulse picker from PHIN (15 kCHF)
- New EO frequency comb front-end and additional items (overall cost ~80 kCHF)
- PhD student with Uppsala (Eva Roikova), started 1st April 2024 to work on this project and integrate the laser into CLEAR.
- 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.
- Variable pulse duration, no RF locking needed

EO frequency comb amplification and freq conversion



EO frequency comb seeder

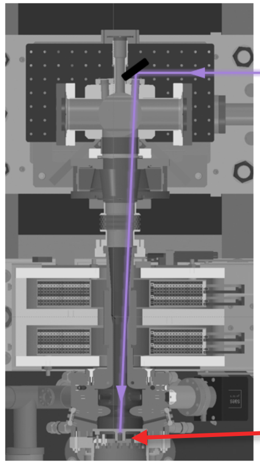


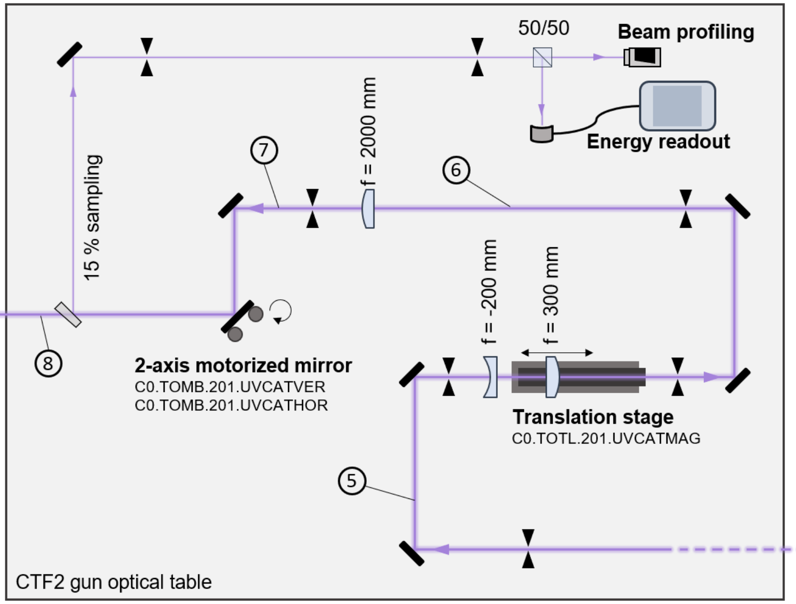


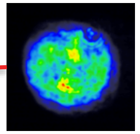
Aiming to finalize prototype by end of 2024

CTF2 e- beamline commissioning

CTF2 Gun





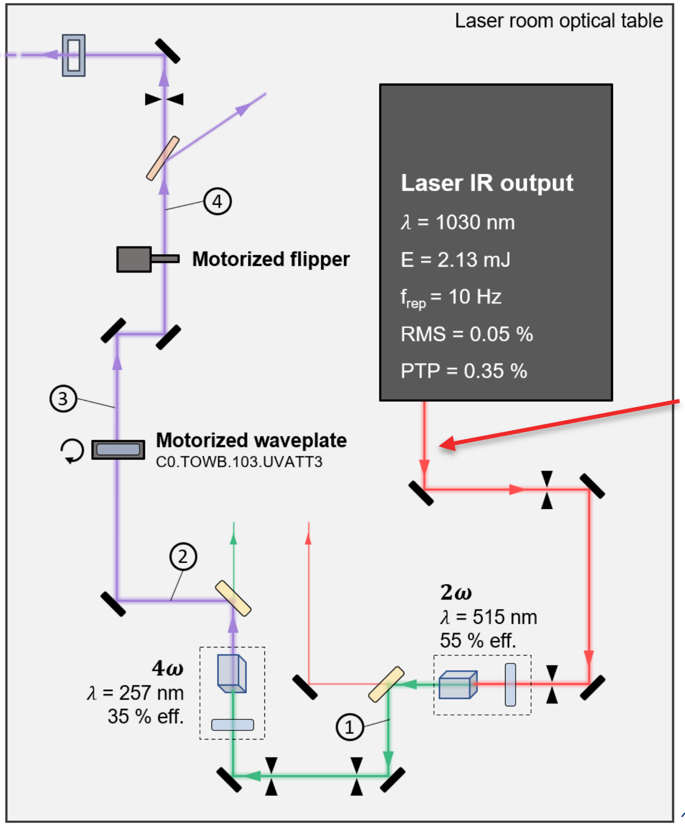


Photocathode

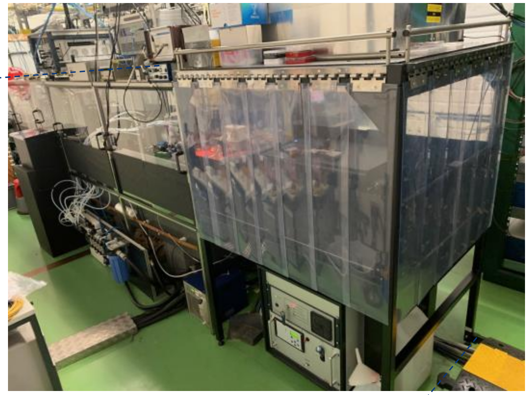
	Legend	
Dichroic mirror		β - BBO crystal
$\lambda/2$ waveplate		Iris
Thin Film Polarizer		Mirror
Beam splitter		Plano-concave/ convex lens
Interlocked shutter		

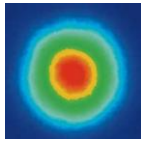
	#	E (μJ)	RMS (%)	PTP (%)
515 nm	1	1240	0.06	0.48
257 nm	2	480	0.09	0.56
	3	435	0.07	0.53
	4	427	0.07	0.45
	5	369	0.16	0.95
	6	304	0.45	5.39
	7	286	0.61	5.89
	8	245	1.04	11.70

Optical setup of CTF2 Photoinjector laser and energy stability



Dedicated laminar flow tent



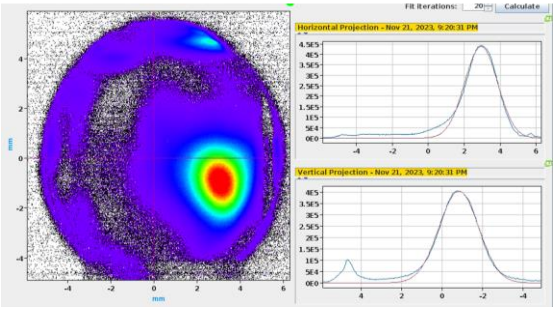


Conversion efficiency:

- IR to green ~60%
- Green to UV ~30%
- Overall ~ **18%**

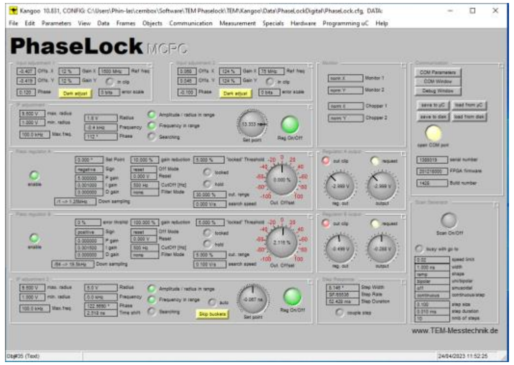
CTF2 e- beamline commissioning

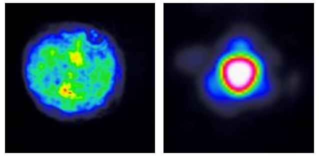
First e- beams from RF gun produced in 2023!

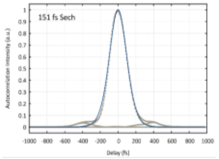


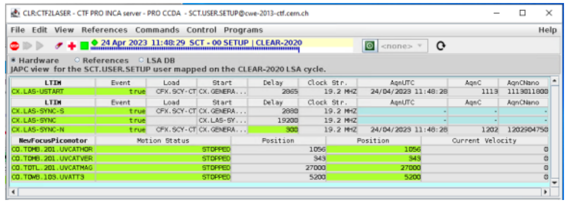
- ✓ 400 pC
- ✓ 6 MeV
- ✓ < 1% energy spread
- ✓ < 1 mm mrad

Locking system and remote controls fully operational, including tunable pulse duration

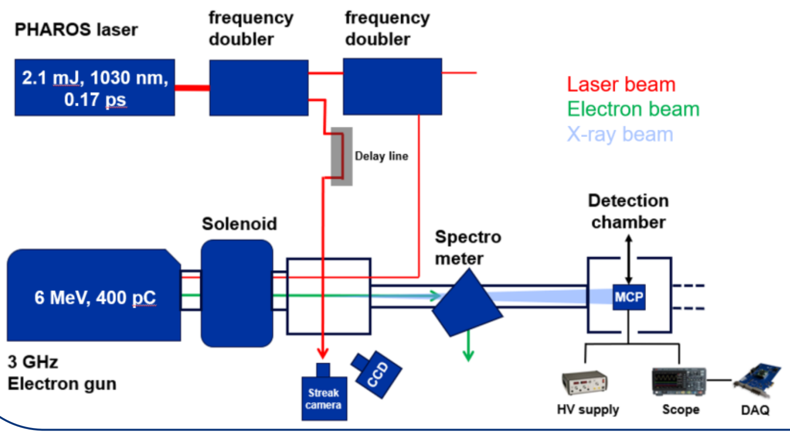


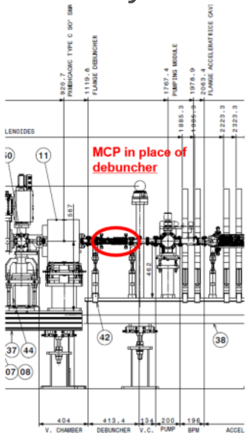






ICS experiment: new high energy IR beamline and x ray detector from LP





- DSO and laser safety systems, beam permit since Q1 2023.
- Full remote operation for laser systems. Running 24/7
- Upgrades in 2024 include commissioning of mJ-class IR beamline for pump-probe experiments
- New load-lock system for RF gun foreseen. Enabling new capabilities at CTF2 thanks to multibunch operation.
- CTF2 will be the AWAKE run 2c photoinjector

Thanks for your attention!

Acknowledgements:

Eric Chevallay, Valentin Fedosseev, Miguel Martinez Calderon, Bruce Marsh, Ralf Rossel, Simone Gilardoni

Recap: level of support needed

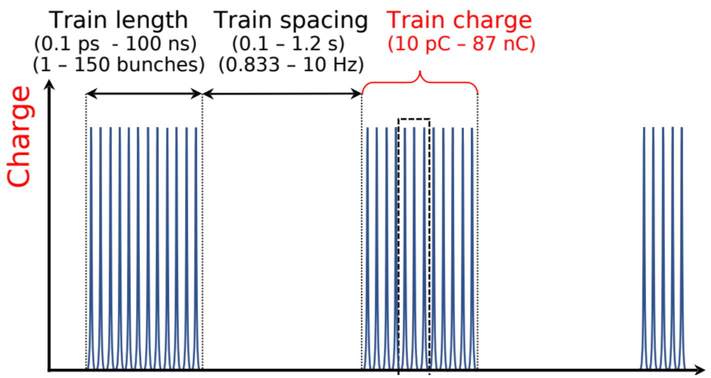
Baseline annual budget

Budget (in kCHF)	2022	2023	2024	2025
CLEAR				
Maintenance of main elements	10	10	10	10
Repairs and spares	25	25	25	25
Upgrade of system capabilities	5	5	5	5
Photoemission lab				
New load-lock system for CTF2		TBD	TBD	
CTF2 photoinjector				
RF locking components	10			
Beam transport optical elements	5			
UV beam diagnostics	5			
Maintenance of main elements	10	10	10	10
Repairs and spares		25	25	25
Upgrades	5	5	5	5
TOTAL	**75**	**80**	**80**	**80**

Personnel support required

Personnel support (FTE/year)	2022	2023	2024	2025
CLEAR				
Operational support and maintenance	0.3	0.3	0.3	0.3
Repairs	0.1	0.1	0.1	0.1
Upgrades	0.1	0.1	0.1	0.1
Photoemission lab				
Photocathode production	0.1	0.2	0.2	0.1
CTF2 photoinjector				
RF locking commissioning	0.2			
Beam transport installation	0.2			
Diagnostic systems	0.1			
Maintenance and operational support	0.4	0.4	0.4	0.4
Repairs	0.1	0.1	0.1	0.1
Upgrades	0.1	0.1	0.1	
Dismantling				0.2
TOTAL	**1.7**	**1.3**	**1.3**	**1.3**
Current allocation				
STAFFs	0.8	0.8	0.8	0.8
Fellows	0.5	0.5	0.5	0.5
TOTAL	**1.3**	**1.3**	**1.3**	**1.3**

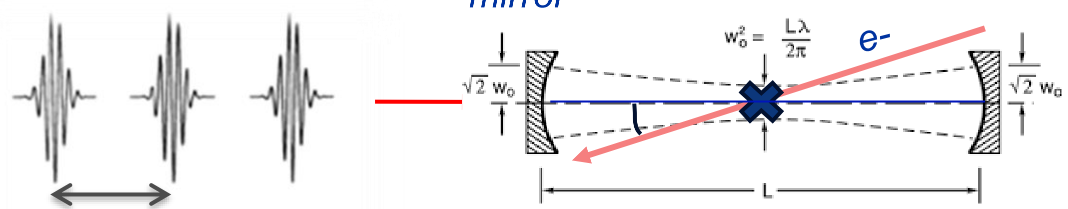
Burst-mode enhancement cavities



Injected laser pulses

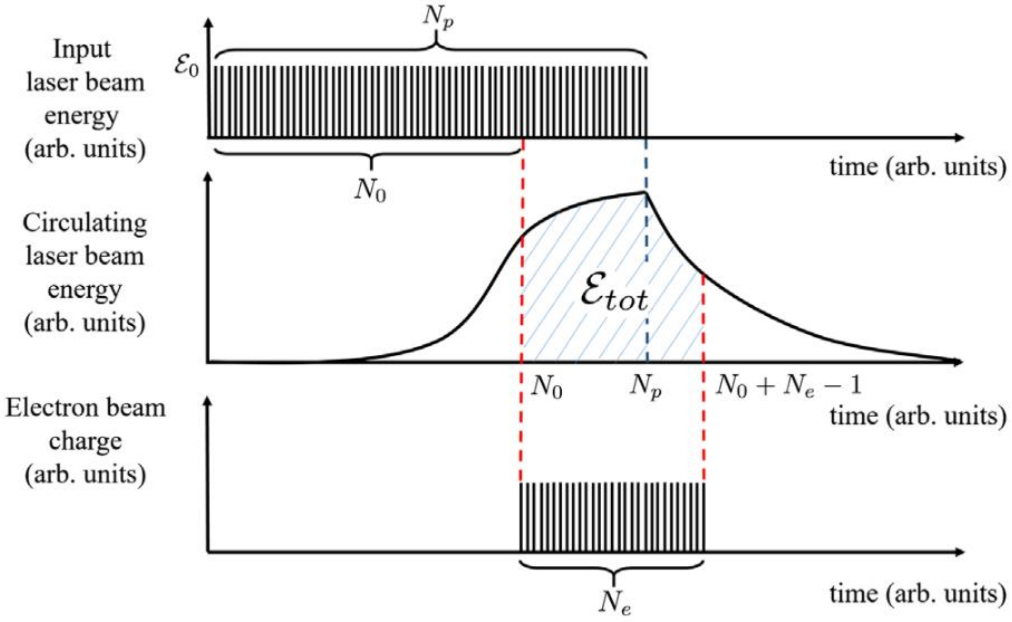
(Coupler) mirror

Spherical mirror



frep

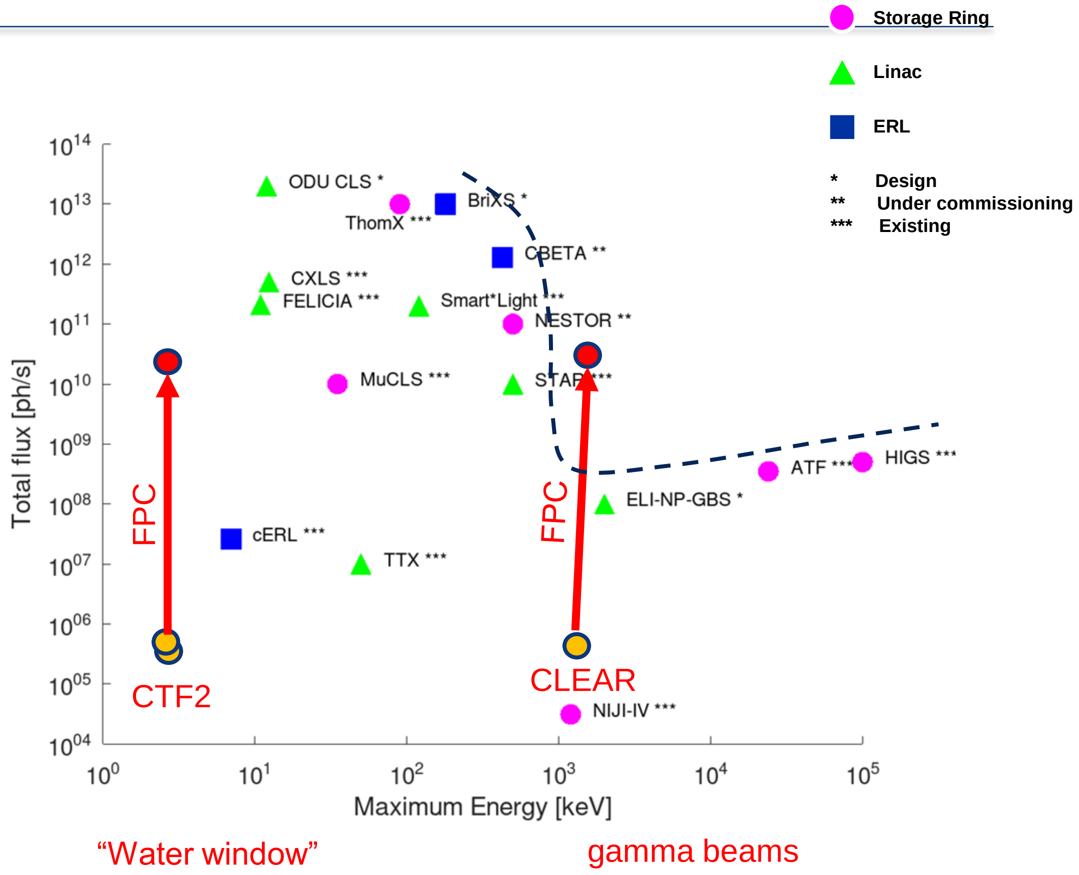
Burst-mode transient energy storage



Impact on ICS @ CLEAR

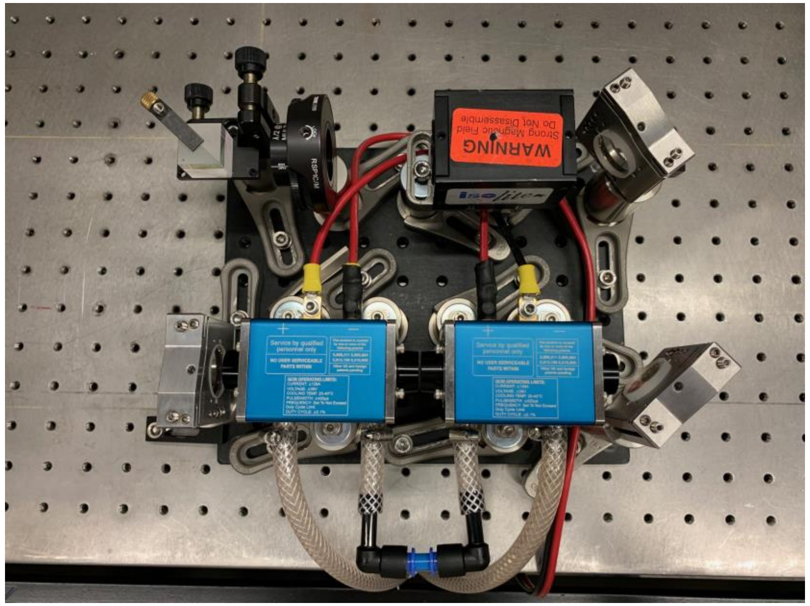
Parameter	Unit	CTF2 + PHAROS + Copper	CTF2 Cs2Te + One Five	CLEAR + CALIFES	CLEAR + PHAROS	CLEAR + One Five
		Single bunch	Train of bunches	Train of bunches	Singe bunch	Train of bunches
Compton edge	keV	0.89	0.88	740	750	740
Electron energy	MeV	7	7	200	200	200
X-ray pulse duration	ps	0.7	6	5	2	7
Ph/bunch		5×10^4	4×10^2	3×10^3	3×10^5	2×10^2
Total flux	Ph/s	5×10^5	3×10^5	9×10^5	3×10^6	3×10^5

Parameter	Unit	CTF2 + OneFive + Cs_2Te + FPC	CLEAR + OneFive + FPC
Bunches/train		80	150
Max Effective gain		60	107
Max Effective energy	J	0.5	0.9
Total flux	ph/s	2×10^{10} @ 890 eV	3×10^{10} @ 740 keV



- Without Fabry-Perot cavity (FPC), ICS experiment doomed to have very low flux.
- FPC requires EO comb as front-end of laser system to be effective.
- Multi-step approach possible, but tied to one option from the beginning.

Acknowledgement: Vlad Musat, Andrea Latina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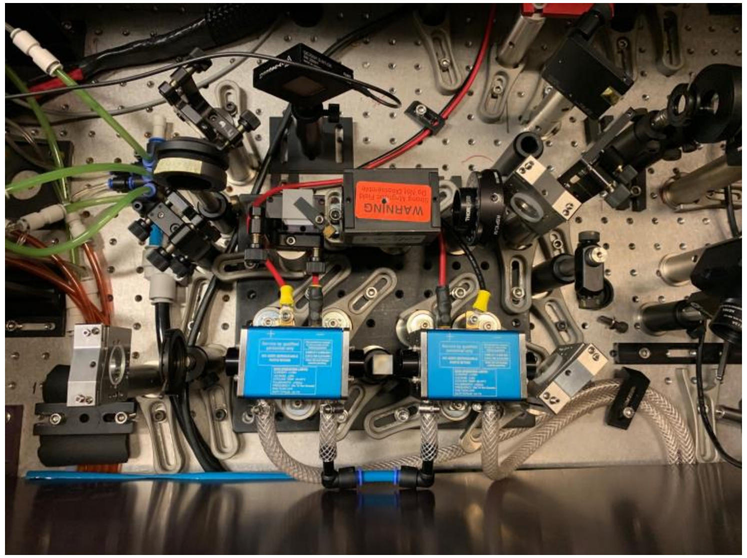
WARNING


ateliers MAITRE
eDrive
ZEROPOINT


HIGH Q LASER
LASER CONTROLLER LC1
REM Iact Iset
Menu
Up Down Cancel Enter
SYNC
ON
Closed Loop
Start/Stop

Energy stability (100 ns trains)

Oscillator output

Parameter	Value
P_avg	321.1 mW
P_max	322.6 mW
P_min	320.2 mW
P_std	0.47%
Pk-Pk	0.75%

Pre-amp output

Parameter	Current value
P_avg	**9.68 W**
P_max	9.75 W
P_min	9.60 W
P_std	**0.37%**
Pk-Pk	**1.53%**

Main amplifier output

Parameter	Value
E_avg	2.726 mJ
E_max	2.781 mJ
E_min	2.697 mJ
E_std	**0.52%**
Pk-Pk	3.08%