

Status of the CLEAR facility at CERN

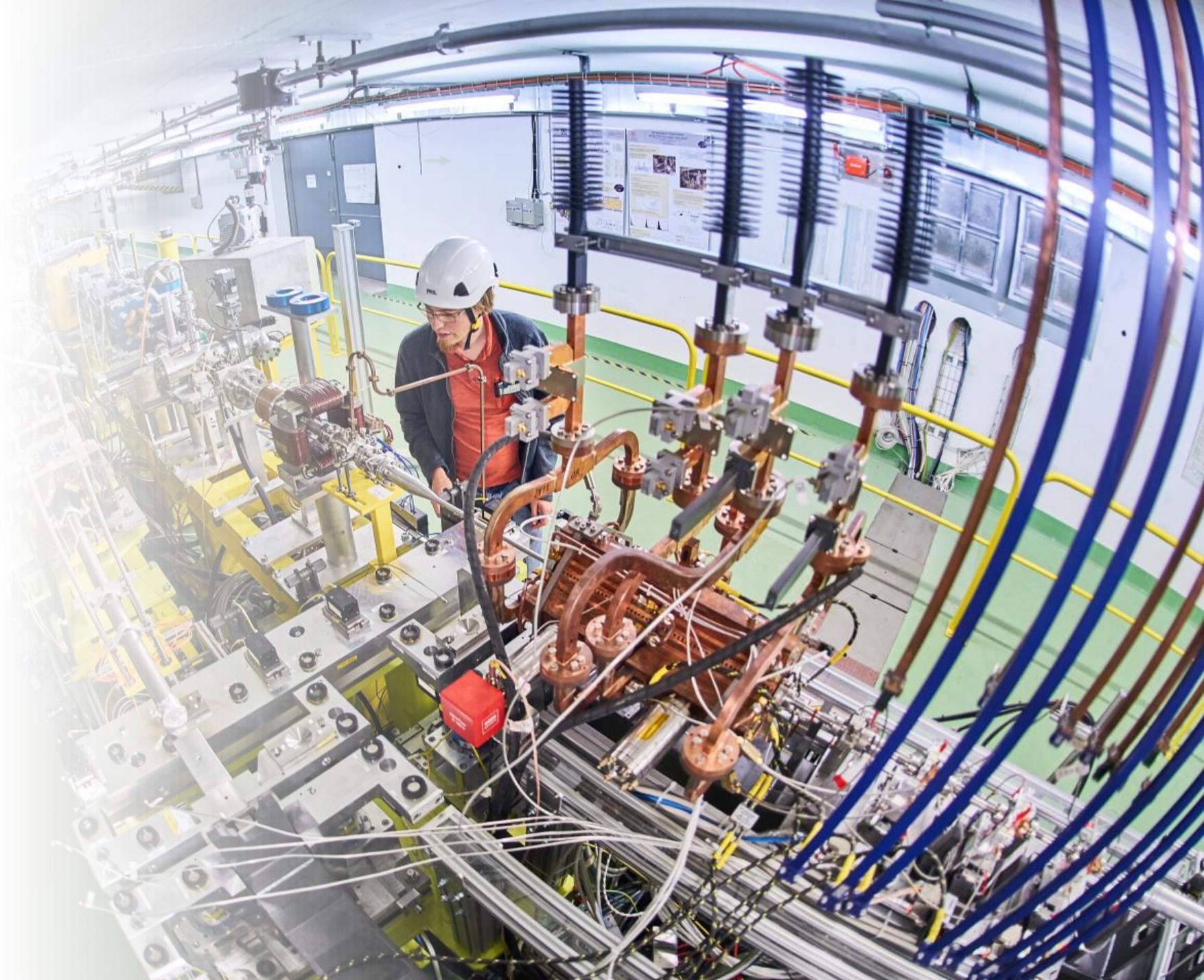


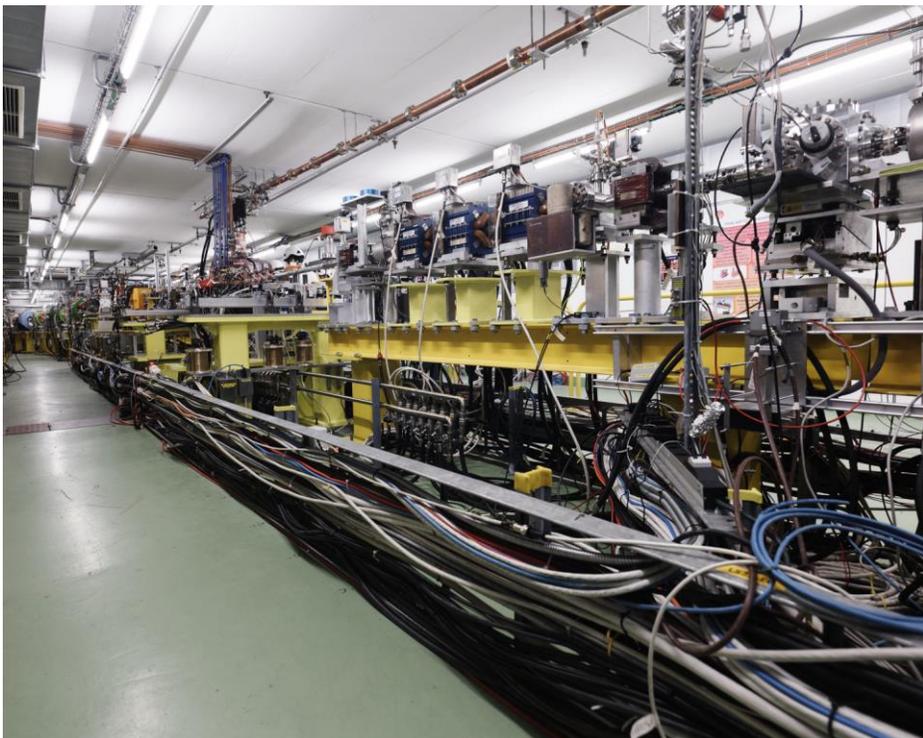
R. Corsini
for the
CLEAR team

CERN Linear
Electron
Accelerator
for Research

Talk outline

- Introduction:
the CLEAR facility
- Status and upgrades
- VHEE/FLASH activities in
CLEAR
- Recent results

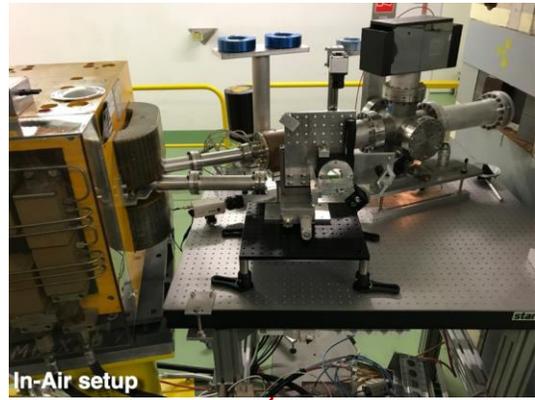




CLEAR is a versatile 200 MeV electron linac followed by a 20 m experimental beamline, operated at CERN from 2017 as a multi-purpose user facility.

Scientific and strategic goals:

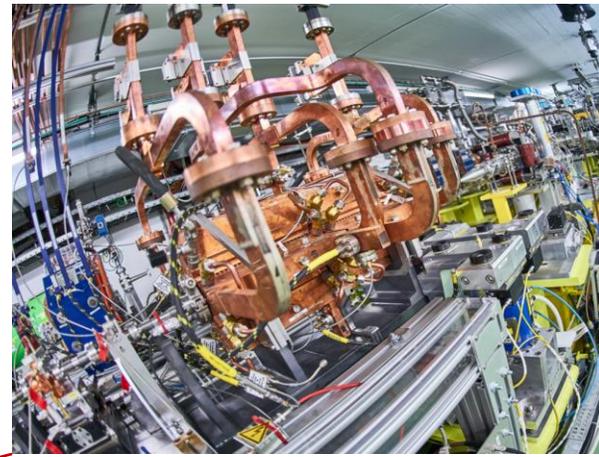
- Providing a test facility at CERN with high **availability**, easy **access** and **high quality e- beams**.
 - Performing **R&D** on **accelerator components**, including **beam instrumentation** prototyping and **high gradient RF** technology
 - Providing an **irradiation facility** with high-energy electrons, e.g. to test electronic components or to investigate **medical applications** (VHEE/FLASH)
 - Performing **R&D** on **novel accelerating techniques** – electron driven **plasma** and **THz** acceleration.
- Maintaining CERN and European **expertise for electron linacs** linked to future collider studies
- Using CLEAR as a **training** infrastructure for the next generation of accelerator scientists and engineers.



In-air test stand

Testing ground for beam diagnostics R&D and THz radiation studies

Irradiation for medical and other applications



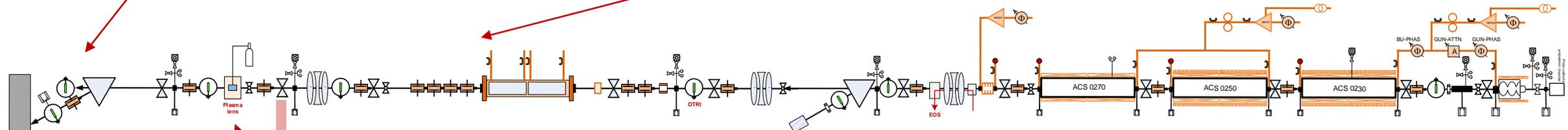
CLIC Test-Stand



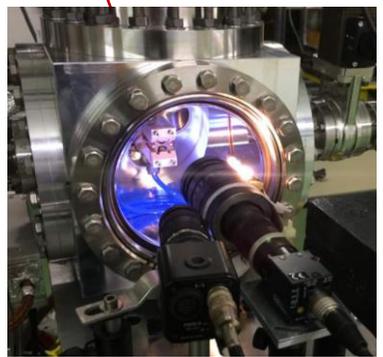
High-gradient and linear collider R&D

+ Beam instrumentation area

CERN Linear Electron Accelerator for Research

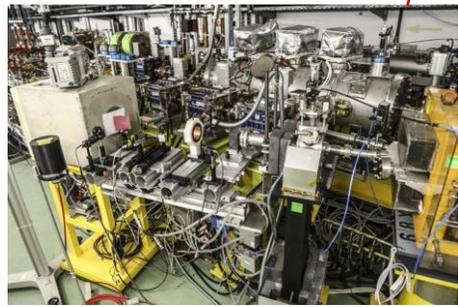


The Plasma Lens Experiment



Novel concepts of plasma-based focusing and acceleration

vesper



VESPER

Beam irradiation facility for studies on radiation damage of electronics and medical applications

CALIFES



CALIFES electron linac

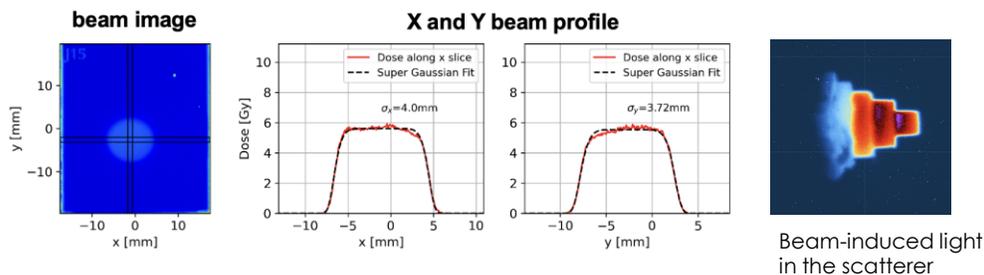
Flexible accelerator providing 200 MeV electron beams to all CLEAR users

Extended parameter range and performances since 2017

- Short bunches
- High charge
- Large energy range
- Stability, beam sizes,...

Beam parameter	Range
Energy	30 – 230 MeV
Energy Spread	< 0.2 % rms (< 1 MeV FWHM)
Bunch Length	0.1 ps – 10 ps rms
Bunch Charge	5 pC – 3 nC
Number of bunches per pulse	1 to ~150
Maximum total pulse charge	80 nC
Normalized emittances	3 μm to 30 μm (bunch charge dependent)
Repetition rate	0.8 to 10 Hz
Bunch spacing	1.5 GHz or 3 GHz

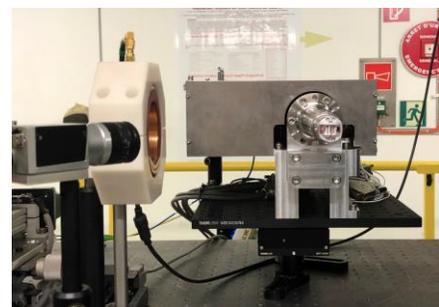
Double-scattering system for uniform beam delivery and real-time dosimetry system now fully operational (CERN/Oxford U.)



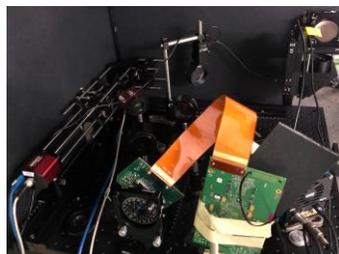
CLEAR Operation 2024

- 30 Experiments
- About 24 User Groups internal/external
- More than 20 external collaborating institutes
- Beam from February 26th to December 15th (with 3 weeks summer stop)
- 39 weeks of operation in total

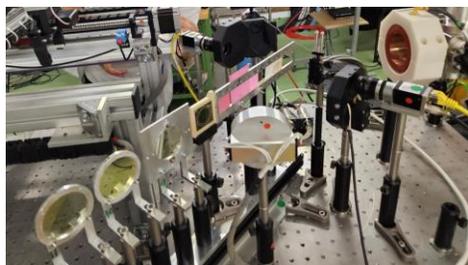
Studies of radiotherapy delivery plan using an anatomical phantom (Manchester University)



Continuation of FCC-ee related studies (e.g., EO longitudinal beam monitor, Karlsruhe)



Emittance measurements based on digital micro-mirror and micro-lens array (Liverpool U.)

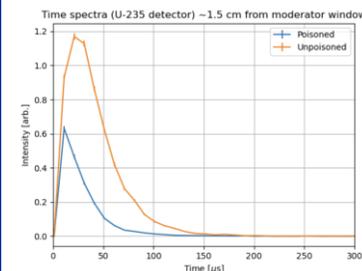


Beam Instrumentation

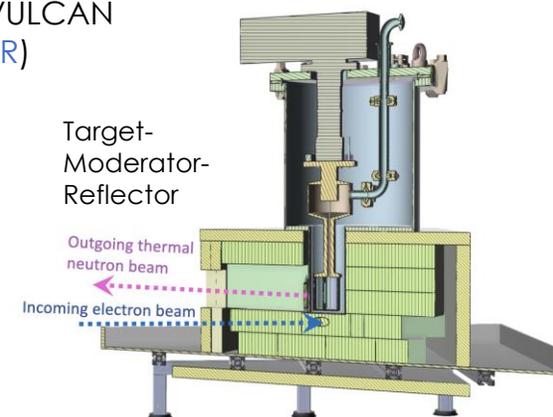
Measurement of scintillator screens response (CERN/BI and Sheffield U.)

First hands-on accelerator course, EURO-LABS

Experimental tests of the neutron Target-Moderator-Reflector for the VULCAN project (DAES/CERN-KT/CLEAR)

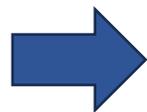


Neutron flux and time-of-flight measurements



A. Lombardi – report to CERN IEFC, August 2024

- “fantastic job with minimal budget”
- “excellent synergy and support of the users”
- “excellent operational efficiency”
- “impressive output and impact”



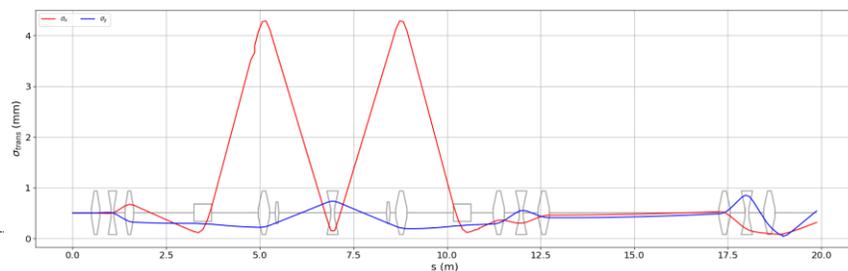
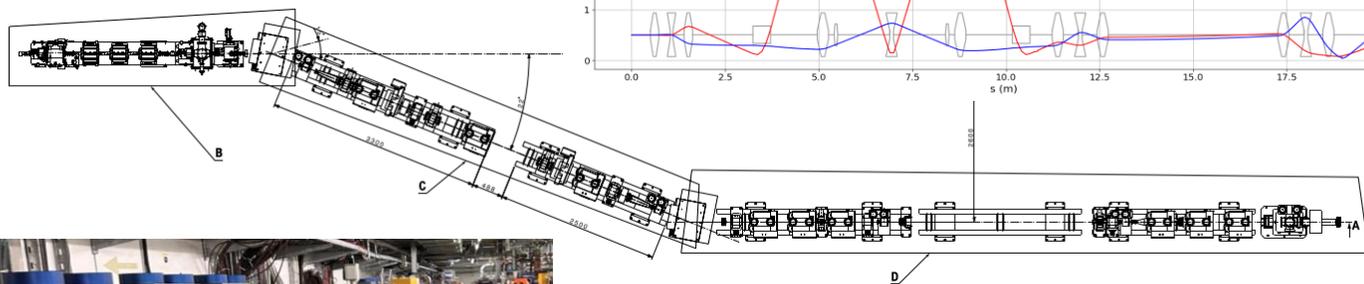
the committee is fully convinced that continued operation of CLEAR beyond 2025 is scientifically justified.

After a successful review held last spring, CLEAR operation has been extended until 2030

(<https://indico.cern.ch/event/1418402/>)

New beam line under completion

beam commissioning from autumn 2025



(a) Intensity (a.u.) vs Time (ns) showing 500 ps pulses.

(b) Intensity (dBm) vs Wavelength (nm) showing a 2 GHz spectrum. Legend: Output with shaping (red), Output without shaping (green), Shaped input (blue).

(c) Intensity (a.u.) vs Delay (ps) showing a measured spectrum (red) with a Sech' fit (dashed) and FT (green). Legend: With spectral shaping (red), Measured (red), Sech' fit (dashed), FT (green). AC width: 270 fs.

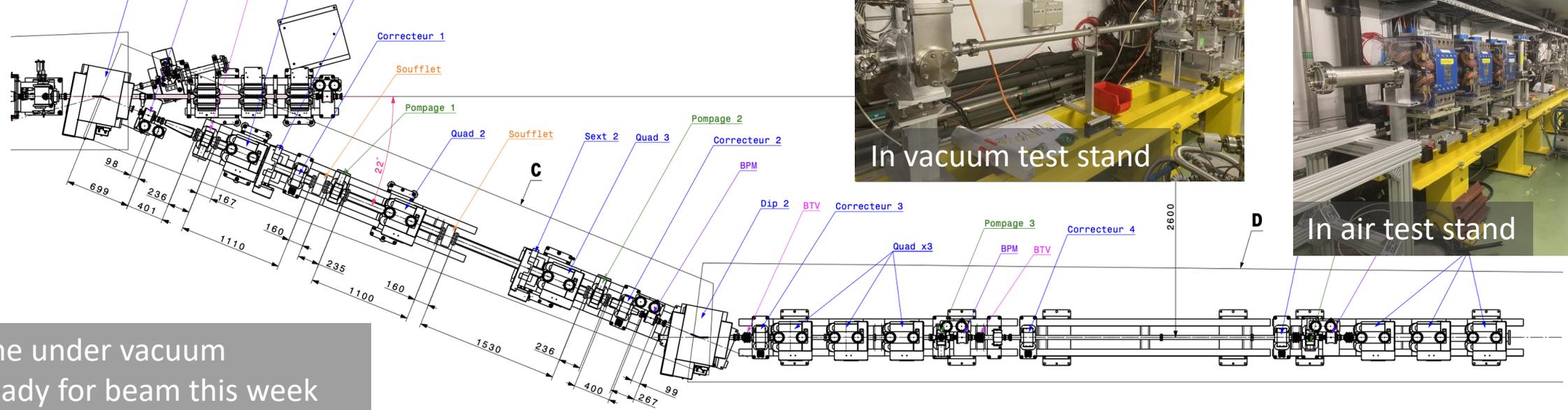
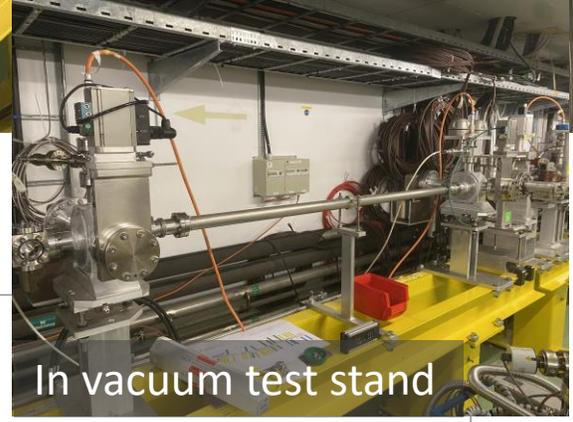
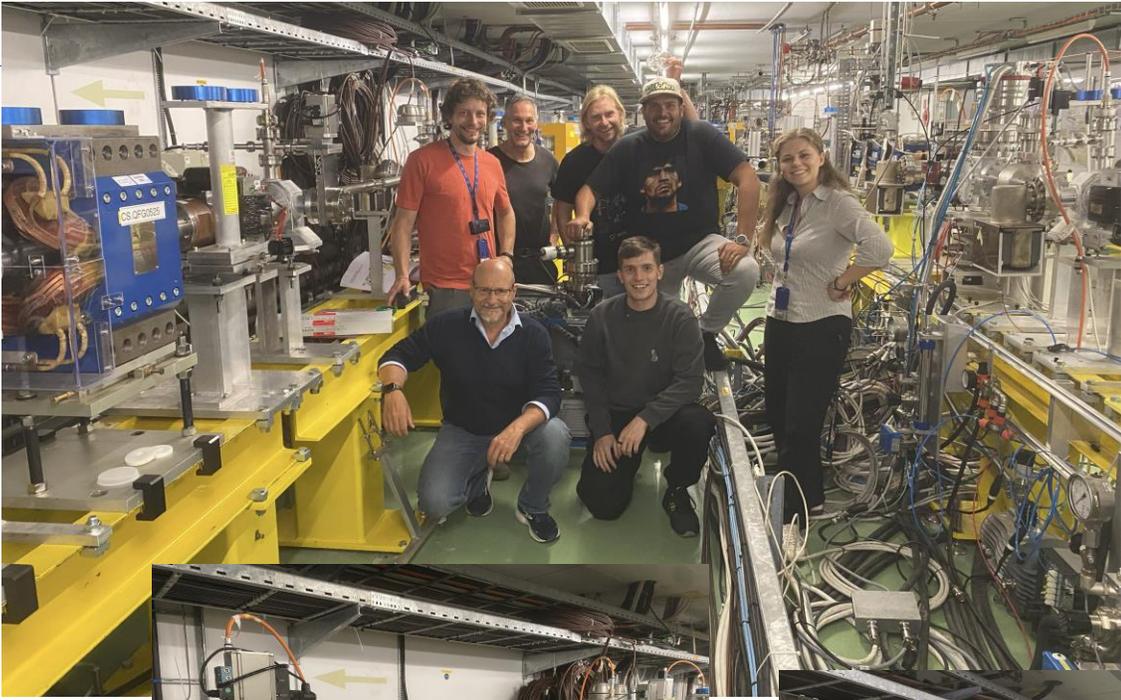
(d) Intensity (a.u.) vs Delay (ps) showing a measured spectrum (red) with an unshaped input (blue) and FT (green). Legend: Without spectral shaping (red), Unshaped input (blue), Measured (red), FT (green).

New EO comb laser front-end

implementation in 2016

AIM: continue and extend the present experimental program – with several improvements already under way (laser, new beam line, consolidation of RF, diagnostics and operation procedures/tools...).

The consolidation program (RF & diags...) will allow efficient runs in the next 5+ years
 The new beam line will improve efficient experiment turn-around and together with the new laser front-end will provide increased flexibility (beam size, time structure...)



Line under vacuum
Ready for beam this week

- Beam started on **March 3rd**
- More than **30 beam time requests** received – **10** on medical activities
- **17** Experiments **successfully completed** so far – **6** on medical activities
- **Six weeks of shutdown** in **August/September** for vacation and to advance the installation of the **2nd beam line** – now completed
- Rest of **September reserved** for recommissioning after the stop, for the initial commissioning of the **2nd beam line** and for machine development
- Restart with users planned for **October 6th**

Methods, Dosimetry and Beam Delivery Techniques

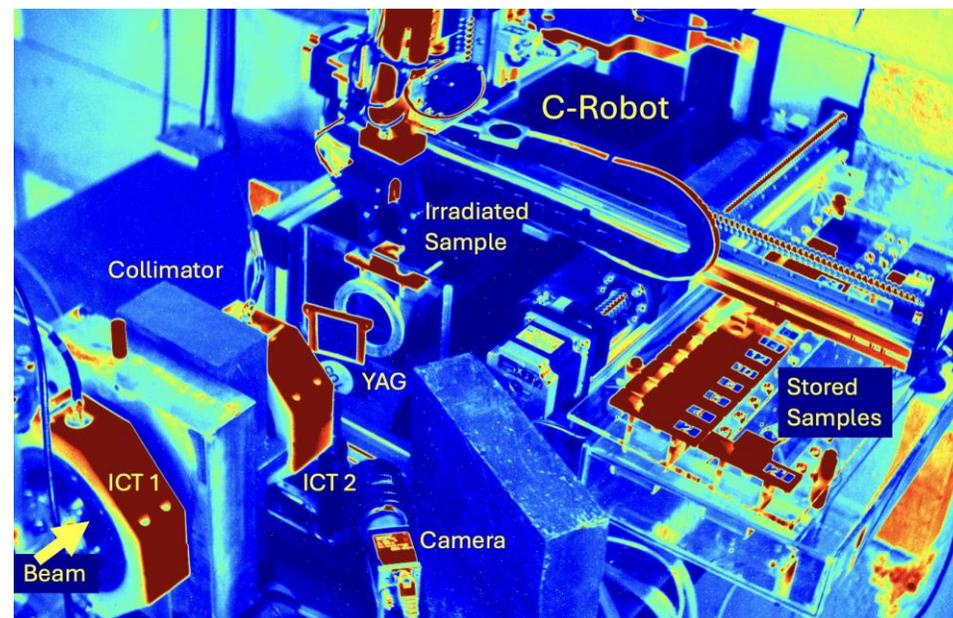
The CLEAR team has developed in the last years methods and tools dedicated to VHEE and FLASH studies, including dosimetry techniques, sample handling, and beam delivery.

- **Radiochromic films** are the main dosimetry tool and have been used routinely in CLEAR.
- Detailed **procedures** for handling and exploiting the films were developed and validated in order to ensure a reliable dosimetry.
- The development of a **robotic system** (the **C-Robot**) allowed for remote handling of a **large number of samples** and is fundamental to avoid frequent accesses to the accelerator hall.
- An **active dosimetry** method based on a YAG scintillating screen and an integrating current transformer has been developed in CLEAR and it is now operational.

Chemistry and biological studies

Several **irradiation experiments** were performed in the last two years in collaboration with external institutes, with the aim to **clarify the mechanisms** at the root of the **FLASH effect**, comparing the effects of UHDR with conventional dose rates on controlled samples.

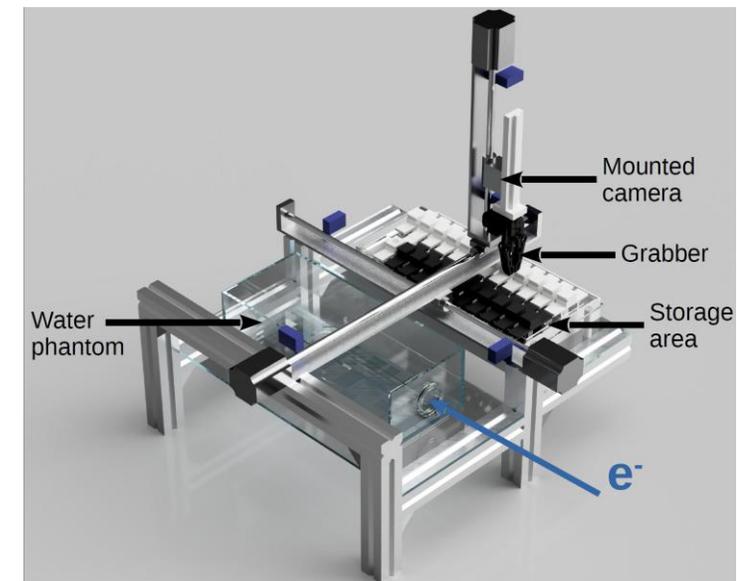
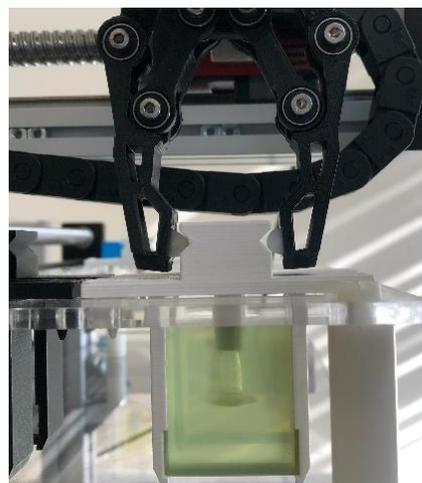
Typical experimental set-up used in CLEAR for chemistry and biological irradiation experiments.



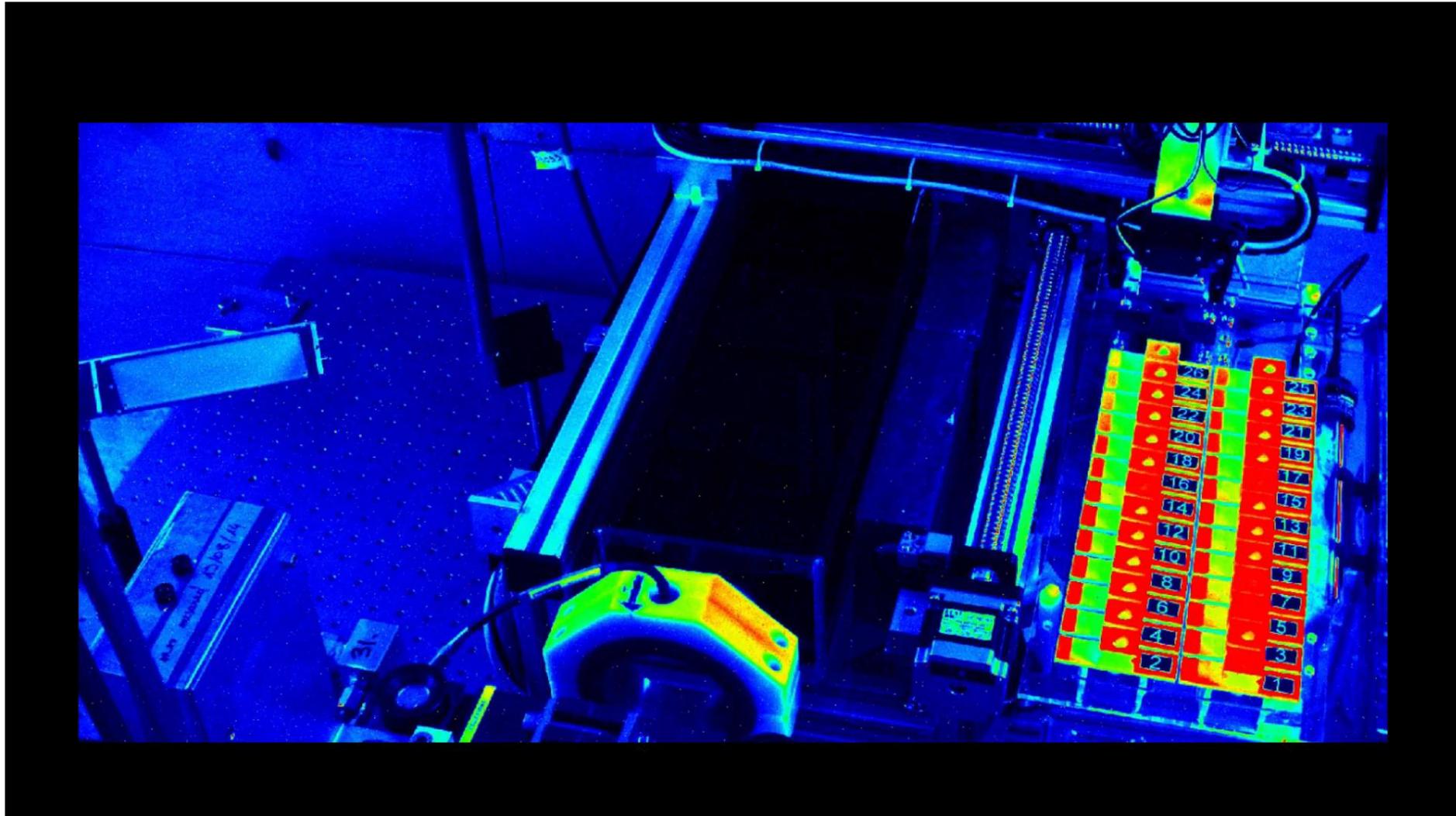
In order to facilitate the precise control of samples for multiple irradiations, the CLEAR-Robot (C-Robot) was designed and built by members of the CLEAR Operation Team.

- It consists of 3 linear stages, 6 limit switches, a 3D-printed grabber, two water tanks and an Arduino board.
- It has a precision in position in 3 axis of 50 μm .
- It is fully remotely controllable from the CERN Technical Network.
- Thanks to a mounted camera, it can also measure the beam sizes and transverse positions at the longitudinal position of the sample.
- It is an open-source project: pictures, 3D renders, drawings and all the codes for the Arduino and the Graphical User Interface can be found on the CLEAR web site.
- Used for all medical applications experiments in CLEAR from 2023.

Holder with films and Eppendorf tube



C-ROBOT



Both clinical radiotherapy applications and pre-clinical testing require a **large, uniform field**. It is not straightforward to obtain this with a VHEE beam.

C. Robertson

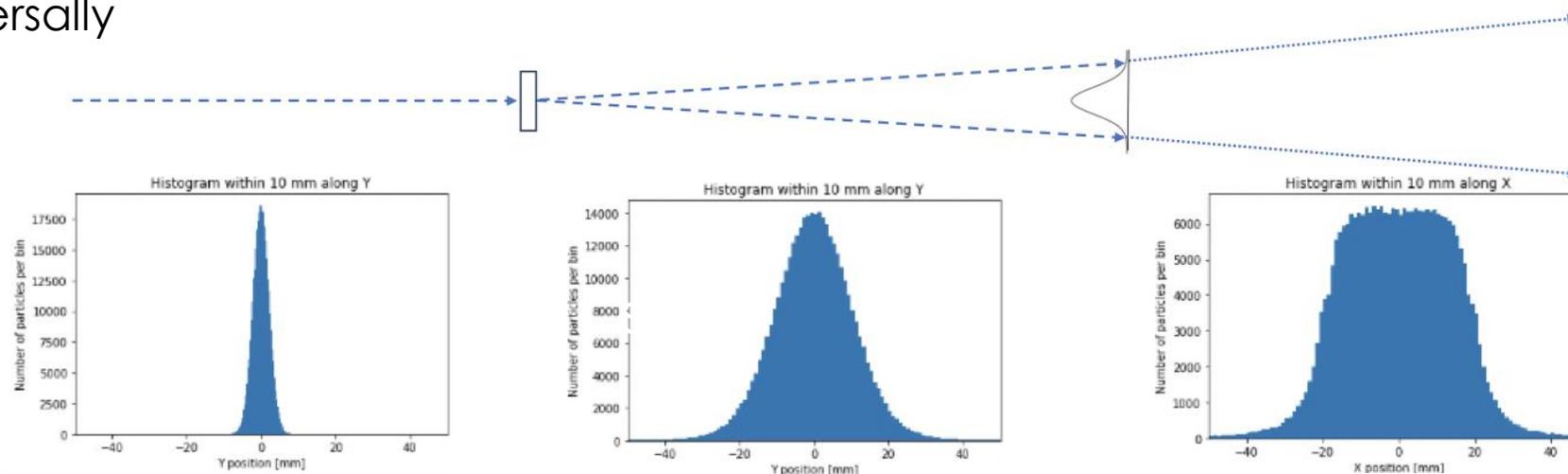


Goal:

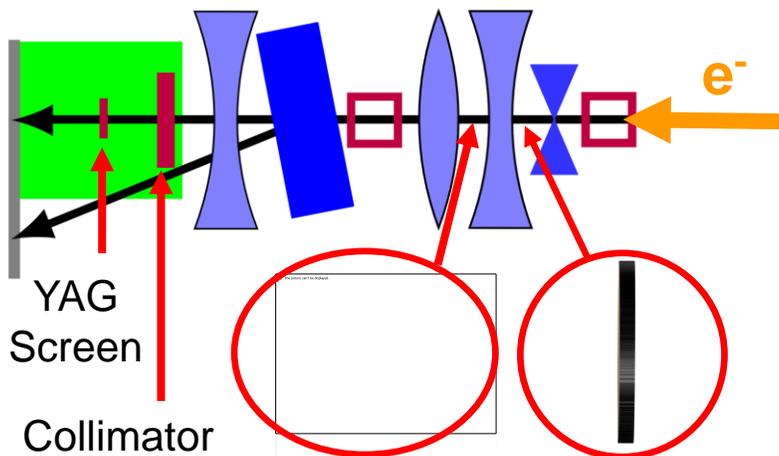
Obtain a **flat transverse beam distribution** at the sample (or at patient's tumor).

Method:

Double scattering foil. Use two scatterers: the first flat and relatively thin, to magnify the gaussian beam, and the second one with a variable thickness (ideally gaussian), to redistribute the beam transversally

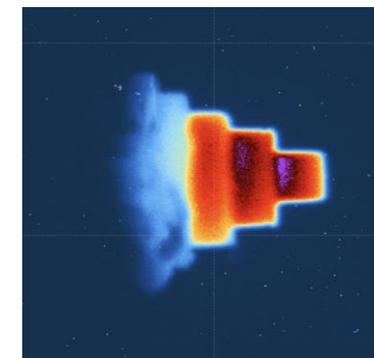
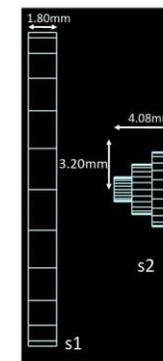


C. Robertson



After some initial tests in-air of the double scatterer system, a full in-vacuum version was installed in CLEAR

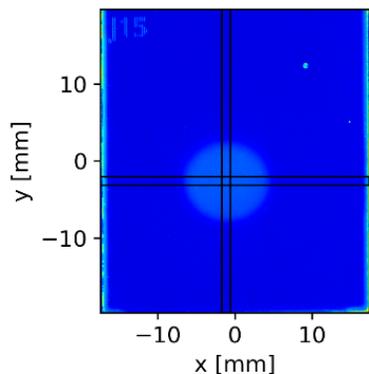
The position and geometry of the scatterers were optimized using GEANT4 simulations



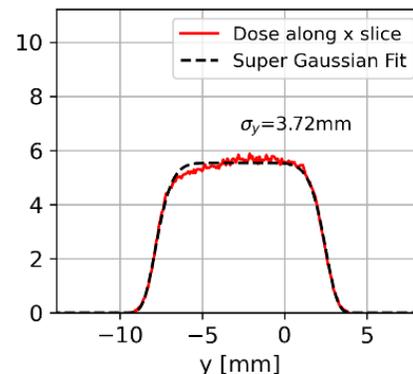
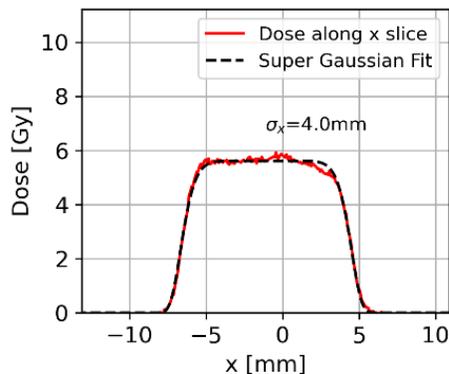
First version of the in-vacuum scatterer

Beam-induced light in the scatterer

beam image



X and Y beam profile



Now routinely used in CLEAR operation

Radiochromic films are the main reference dosimetry tool and have been used routinely in CLEAR.

Detailed procedures for handling and exploiting the films were developed and validated in order to ensure a reliable dosimetry.



- Passive dosimetry method considered to be dose-rate independent.
- Widely used as reference dosimetry for many UHDR experiments.
 - Used at CLEAR for almost all UHDR studies.
- Calibrated to low energy clinical electron beam at CHUV and analysed using custom analysis code.

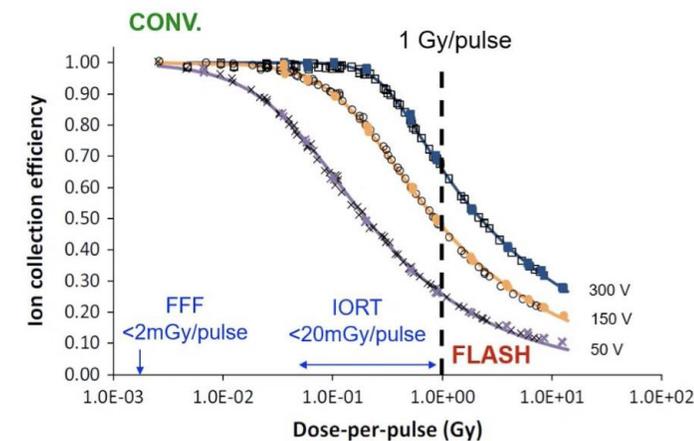
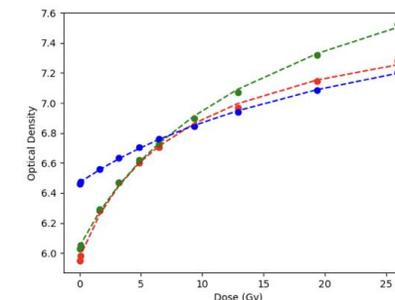
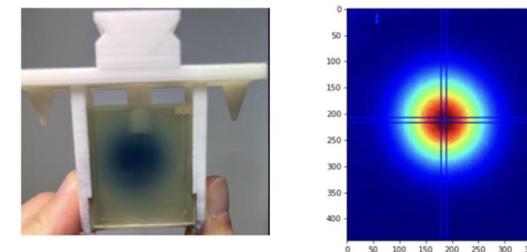


J. Bateman

Clinical use of VHEE/FLASH radiotherapy requires fast (possibly real-time) dosimetry, however standard methods (e.g., ionization chambers) are not well adapted to UHDR regime (ion recombination, nonlinear response)

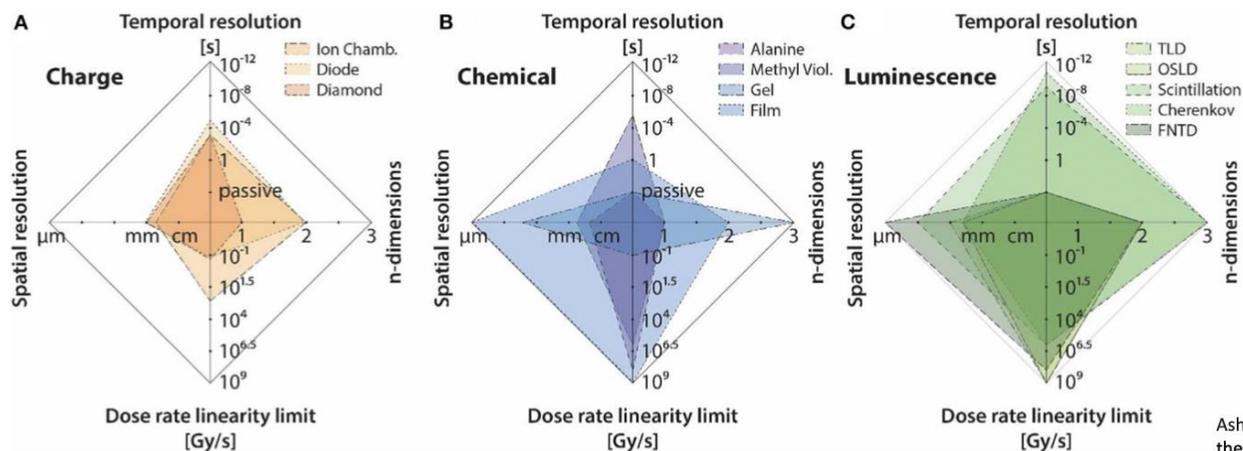


- Ionisation chambers saturate in UHDR conditions required for FLASH.
- Correction factors can account for decrease in ion collection efficiency at UHDR but introduce large uncertainties.
- Collection time of transmission ICs (order of μs) too slow for FLASH beam monitoring.



Petersson et al., Med Phys 44 (2017) 1157

- Modified ionisation chamber geometry and design, e.g., ultra-thin plane parallel ion chambers
- Solid-state detectors e.g., diamond detectors, Si/SiC detectors
- Radioluminescence detectors –scintillators, fibres, gas monitors, screens, Cherenkov.
- Accelerator Beam Instrumentation - current transformers, pick-up monitors etc.



J. Bateman

Ashraf, M. et al. Dosimetry for FLASH Radiotherapy: A Review of Tools and the Role of Radioluminescence and Cherenkov Emission (2020).

Alternative methods for real time dosimetry adapted to UHDR have been studied at CLEAR by various collaborations. A very promising development has been the use of optical fiber arrays, developed in CLEAR by J. Bateman from Oxford University.

Several options for the type and angle of the fiber and for the light detector used were explored using single fibers, before developing a full prototype.

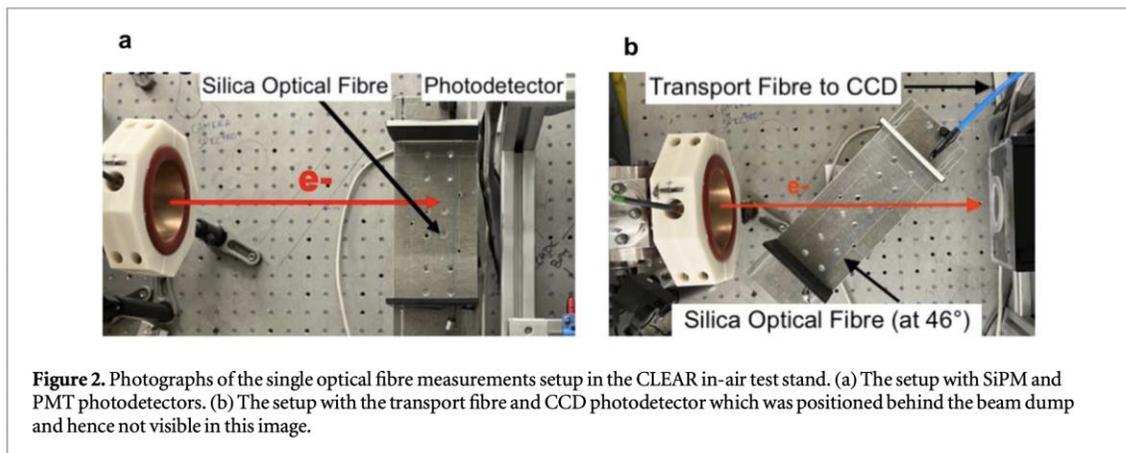


Figure 2. Photographs of the single optical fibre measurements setup in the CLEAR in-air test stand. (a) The setup with SiPM and PMT photodetectors. (b) The setup with the transport fibre and CCD photodetector which was positioned behind the beam dump and hence not visible in this image.

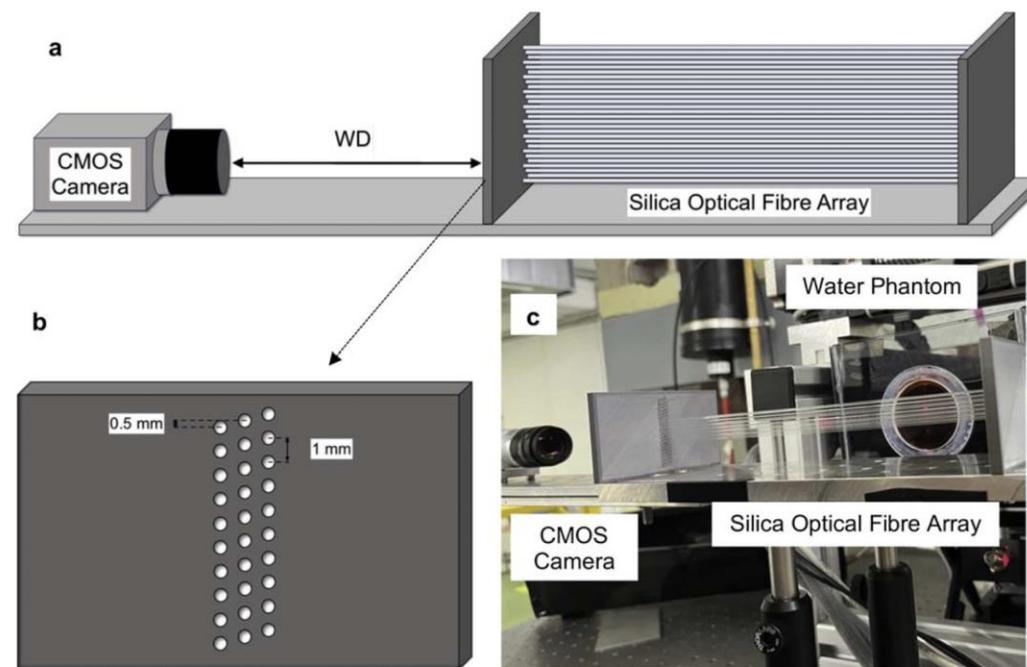


Figure 3. (a) Schematic of the FOFM assembly with the CMOS cameras and silica optical fibre array, where the working distance (WD) between the edge of the lens and the fibres is 105 mm. (b) Schematic of 3D printed optical fibre support displaying the vertical arrangement of the silica fibres. (c) Photograph of the optical fibre array of the FOFM, consisting of 28 fused silica optical fibres, installed in the in-air test stand at the CLEAR facility.

Development of a novel fibre optic beam profile and dose monitor for very high energy electron radiotherapy at ultrahigh dose rates

Joseph J Bateman¹ , Emma Buchanan², Roberto Corsini², Wilfrid Farabolini², Pierre Korysko^{1,2}, Robert Garbrecht Larsen^{2,3} , Alexander Malyzhenkov², Iñaki Ortega Ruiz², Vilde Rieker^{2,4}, Alexander Gerbershagen³ and Manjit Dosanjh^{1,2}  [▲ Hide full author list](#)

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[Physics in Medicine & Biology, Volume 69, Number 8](#)



Optical fiber arrays tests, performed in CLEAR by J. Bateman from Oxford University, confirmed a **good linearity** over a wide range of doses and dose rates, and the **capability of resolving the transverse dose distribution** with good resolution.

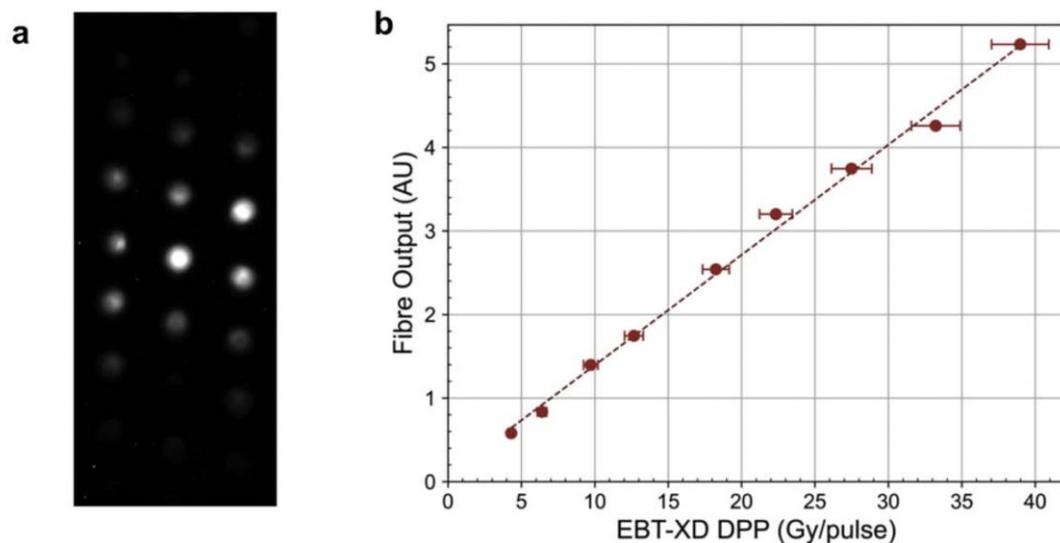


Figure 8. (a) An example image of the fibre signal measured by the CMOS camera (after noise removal) following a 30 nC pulse. (b) The dose-per-pulse (DPP) response of the FOFM between 4.3 and 39.0 Gy/pulse, with the same gain settings on the CMOS camera for all measurements ($R^2 = 0.996$, $\chi^2_\nu = 0.028$, $P(\chi^2) = 1.000$).

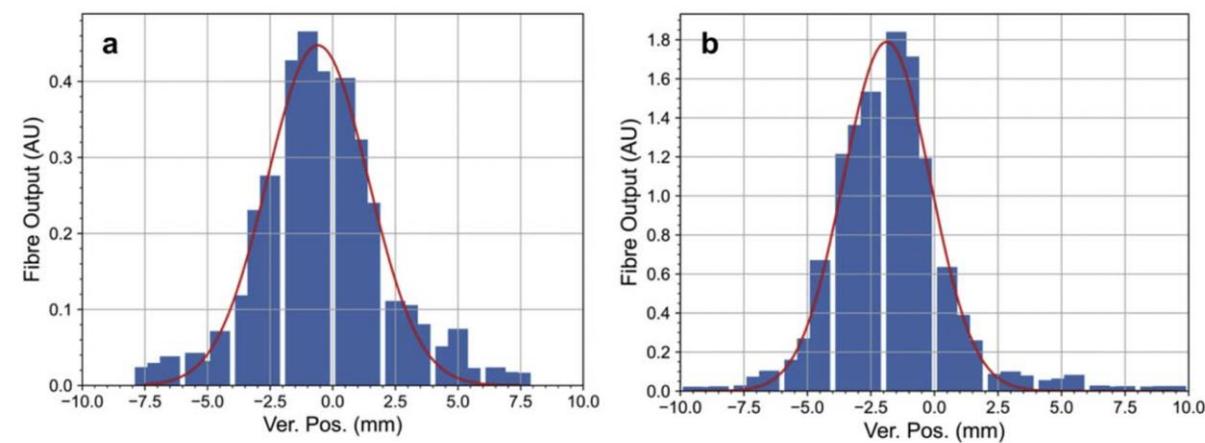
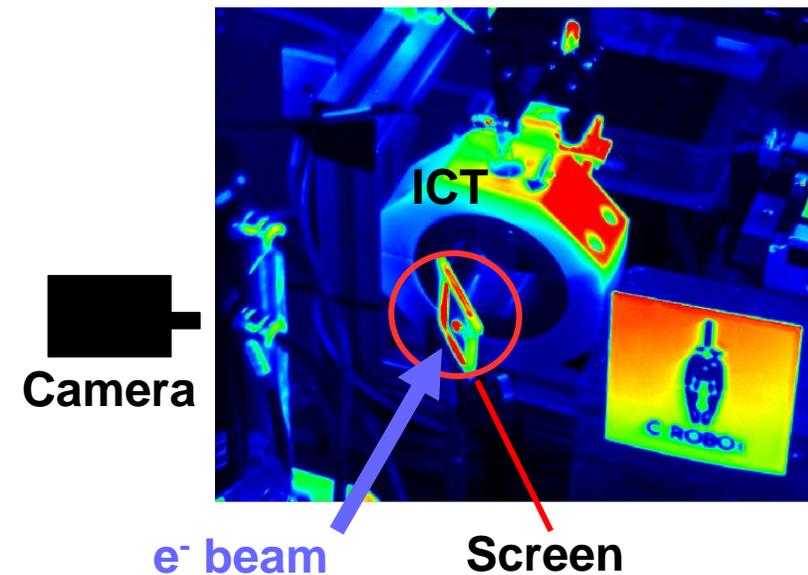
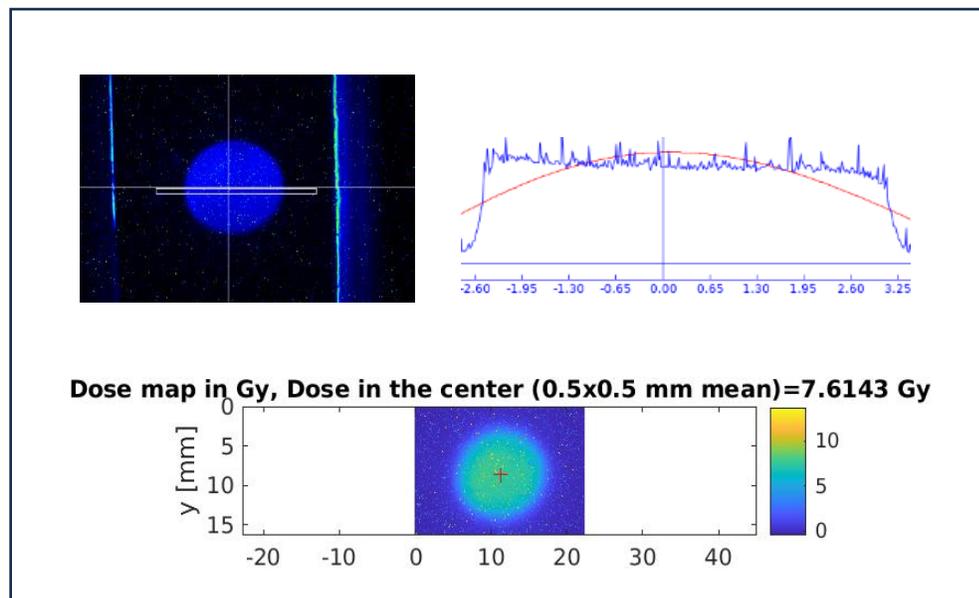
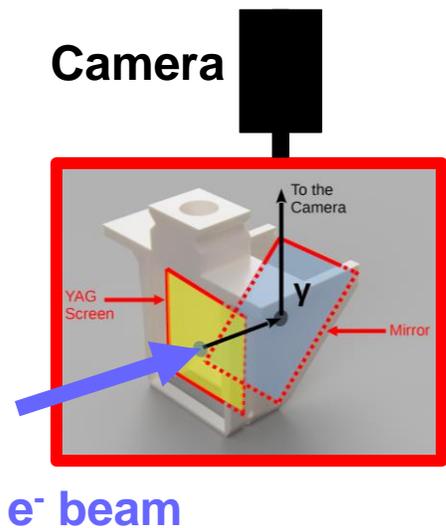


Figure 11. Vertical profile measurements made by the FOFM for (a) a 1 nC; and (b) a 10 nC electron pulse at 200 MeV with a Gaussian fit applied (red line).

In CLEAR we developed as well a **fast dosimetry method** by measuring the beam charge with an **ICT** and the beam size with a **scintillating YAG screen**. The samples are then irradiated at the same exact location. Dose measurements were calibrated using gafchromic films.

A similar method is being developed using a thin scintillating screen in air in front of the water phantom for **real-time dose measurement**.

Now routinely used in CLEAR operation



V. Rieker, A. Malyzhenkov,
J. Bateman



In less than 8 years of operation, the experimental activities carried out in the CLEAR user facility have generated:

- 29 Journal papers (12 on VHEE)
- 45 Conference papers (18 on VHEE)
- More than 16 completed PhD thesis, plus several ongoing.
- More than 17 outreach publications in specialized journals, press releases, ...

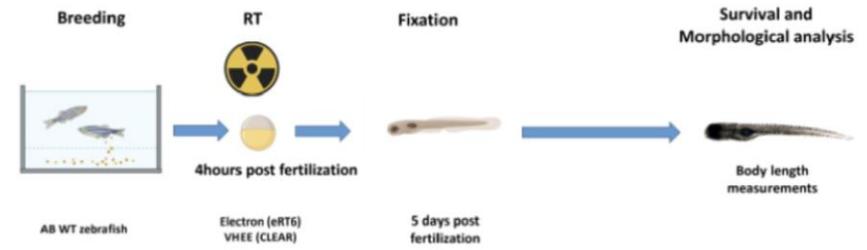
<https://clear.cern/content/publications>

Journal papers:

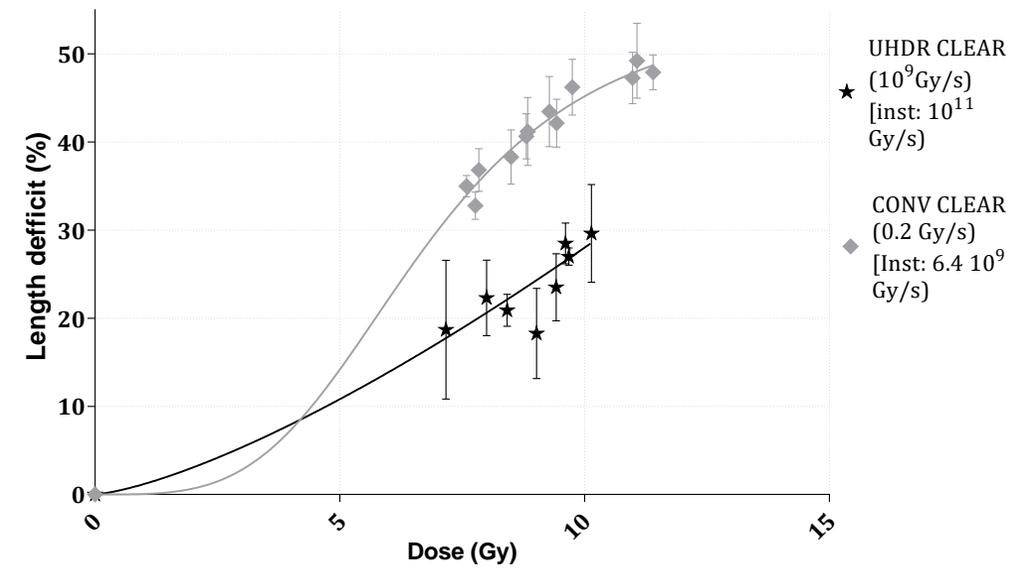
- **Radiotherapy and Oncology - May 2025:** Modification of the microstructure of the CERN- CLEAR-VHEE beam at the picosecond scale modifies ZFE morphogenesis but has no impact on hydrogen peroxide production ([link](#)).
- **Phys. Rev. Research - Feb. 2025:** Design and experimental verification of a bunch length monitor based on coherent Cherenkov diffraction radiation ([link](#)).
- **Nucl. Instrum. Methods Phys. Res., Sect. A - Sep. 2024:** Active dosimetry for VHEE FLASH radiotherapy using beam profile monitors and charge measurements ([link](#)).
- **Nature Scientific Reports - Jun. 2024:** VHEE FLASH sparing effect measured at CLEAR, CERN with DNA damage of pBR322 plasmid as a biological endpoint ([link](#)).
- **Nature Scientific Reports - May. 2024:** CERN-based experiments and Monte-Carlo studies on focused dose delivery with very high energy electron (VHEE) beams for radiotherapy applications ([link](#)).
- **Physics in Medicine & Biology - Apr. 2024:** Development of a novel fibre optic beam profile and dose monitor for very high energy electron radiotherapy at ultrahigh dose rates ([link](#)).
- **Physics Medicine & Biology - Feb. 2024:** Mini-GRID radiotherapy on the CLEAR very-high-energy electron beamline: collimator optimization, film dosimetry, and Monte Carlo simulations. ([link](#)).
- **IEEE Sensors Journal - Jan. 2024:** Plastic scintillator dosimetry of ultrahigh dose-rate 200 MeV electrons at CLEAR ([link](#)).
- **IEEE Transactions on Nuclear Science - Aug. 2023:** Analysis of the Radiation Field Generated by 200-MeV Electrons on a Target at the CLEAR Accelerator at CERN ([link](#)).
- **IEEE Transactions on Nuclear Science - Mar. 2022:** Analysis of the Photoneutron Field Near the THz Dump of the CLEAR Accelerator at CERN With SEU Measurements and Simulations ([link](#)).
- **Physical Review Accelerators and Beams - Dec. 2021:** Strong focusing gradient in a linear active plasma lens ([link](#)).
- **Biomed. Phys. Eng. Expr. - Dec. 2021:** VHEE beam dosimetry at CERN Linear Electron Accelerator for Research under ultra-high dose rate conditions ([link](#)).
- **IEEE Transactions on Nuclear Science - Mar. 2021:** Electron-Induced Upsets and Stuck Bits in SDRAMs in the Jovian Environment ([link](#)).
- **Physics Letters A - Mar. 2021:** Diffractive shadowing of coherent polarization radiation ([link](#)).
- **Nature Communications Physics - Feb. 2021:** An experimental study of focused very high energy electron beams for radiotherapy ([link](#)).
- **Nature Scientific Reports - Feb. 2021:** Evaluating very high energy electron RBE from nanodosimetric pBR322 plasmid DNA damage ([link](#)).
- **Nuclear Instruments and Methods in Physics Research Section B - Nov. 2020:** Influence of heterogeneous media on Very High Energy Electron (VHEE) dose penetration and a Monte Carlo-based comparison with existing radiotherapy modalities ([link](#)).
- **IEEE Transactions on Instrumentation and Measurement - Jul. 2020:** A Measurement Method based on RF Deflector for Particle Bunch Longitudinal Parameters in Linear Accelerators ([link](#)).
- **Nature Scientific Reports - Jun. 2020:** The challenge of ionisation chamber dosimetry in ultra-short pulsed high dose-rate Very High Energy Electron beams ([link](#)).
- **Nature Scientific Reports - May 2020:** Enhancing particle bunch-length measurements based on Radio Frequency Deflector by the use of focusing elements ([link](#)).
- **Physical Review Accelerators and Beams - Feb. 2020:** Noninvasive bunch length measurements exploiting Cherenkov diffraction radiation ([link](#)).
- **Nucl. Instr. and Meth. in Physics Research Sect. B - Oct. 2019:** A magnetic spectrometer to measure electron bunches accelerated at AWAKE ([doi](#)).
- **Physical Review Accelerators and Beams - Feb. 2019:** Beam-based sub-THz source at the CERN linac electron accelerator for research facility ([link](#)).
- **IEEE Transactions on Nuclear Science - Jan. 2019:** Mechanisms of Electron-Induced Single-Event Latchup ([link](#)).
- **Physical Review Letter - Nov. 2018:** Emittance Preservation in an Aberration-Free Active Plasma Lens ([link](#)).
- **IEEE Transactions on Nuclear Science - Jun. 2018:** Mechanisms of Electron-Induced Single-Event Upsets in Medical and Experimental Linacs ([link](#)).
- **Physical Review Letter - Feb. 2018:** Experimental Observation of “Shadowing” in Optical Transition Radiation ([link](#)).
- **Nuclear Instruments and Methods in Physics Research Section A - Nov. 2018:** Overview of the CLEAR plasma lens experiment ([link](#)).
- **IEEE Transactions on Nuclear Science - Jun. 2017:** High-Energy Electron-Induced SEUs and Jovian Environment Impact ([link](#)).

Goal :

Measure the response effect to dose and dose rate on zebra fish embryos with VHEE.

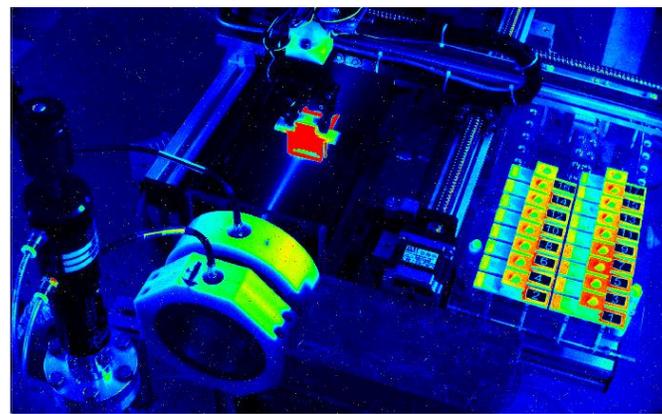
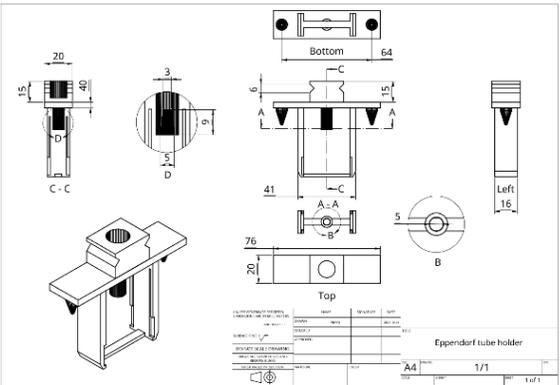


Irradiate fertilized eggs with different doses and dose rates: UHDR (Ultra High Dose Rate) and CDR (Conventional Dose Rate) and measure the length deficit.



First observation of FLASH sparing effect with a VHEE beam!

M-C. Vozenin, H. Kacem, J. Ollivier, L. Kunz ...



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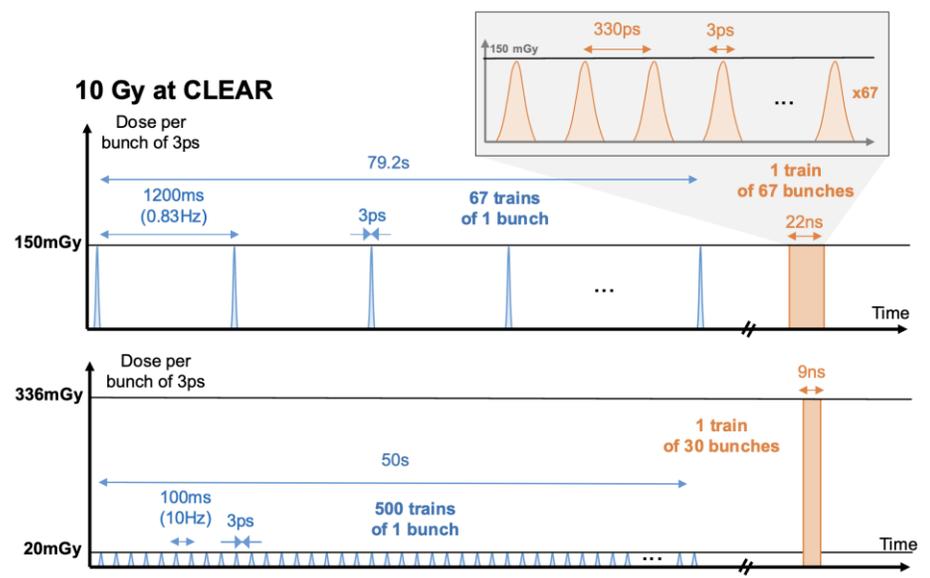
journal homepage: www.thegreenjournal.com



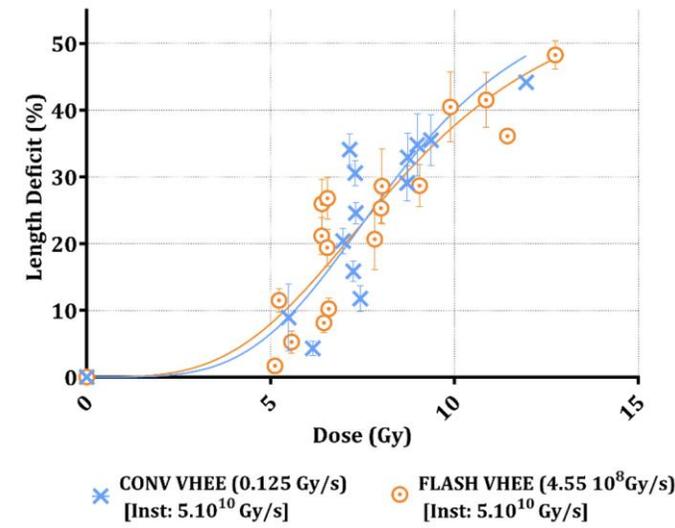
Original Article

Modification of the microstructure of the CERN- CLEAR-VHEE beam at the picosecond scale modifies ZFE morphogenesis but has no impact on hydrogen peroxide production

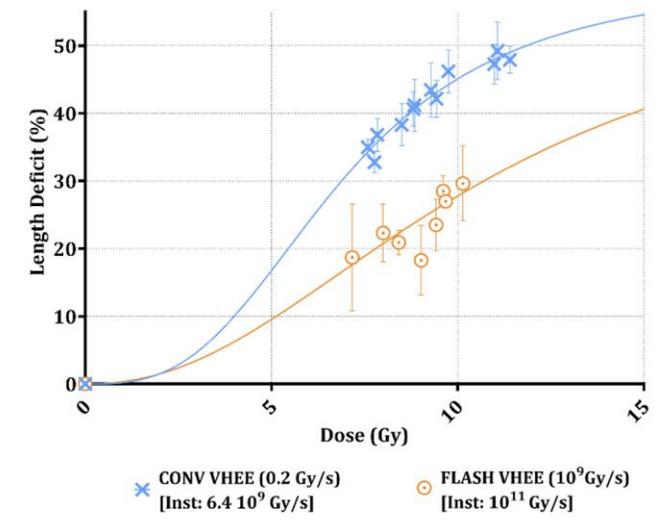
Houda Kacem ^{a,b,c}, Louis Kunz ^{a,b}, Pierre Korysko ^{d,e}, Jonathan Ollivier ^{a,b,c}, Pelagia Tsoutsou ^{a,b}, Adrien Martinotti ^c, Vilde Rieker ^{d,f}, Joseph Bateman ^{d,e}, Wilfrid Farabolini ^d, Gérard Baldacchino ^{g,h}, Billy W. Loo Jr. ^{i,j}, Charles L. Limoli ^k, Manjit Dosanjh ^{d,e}, Roberto Corsini ^d, Marie-Catherine Vozenin ^{a,b,c,*}



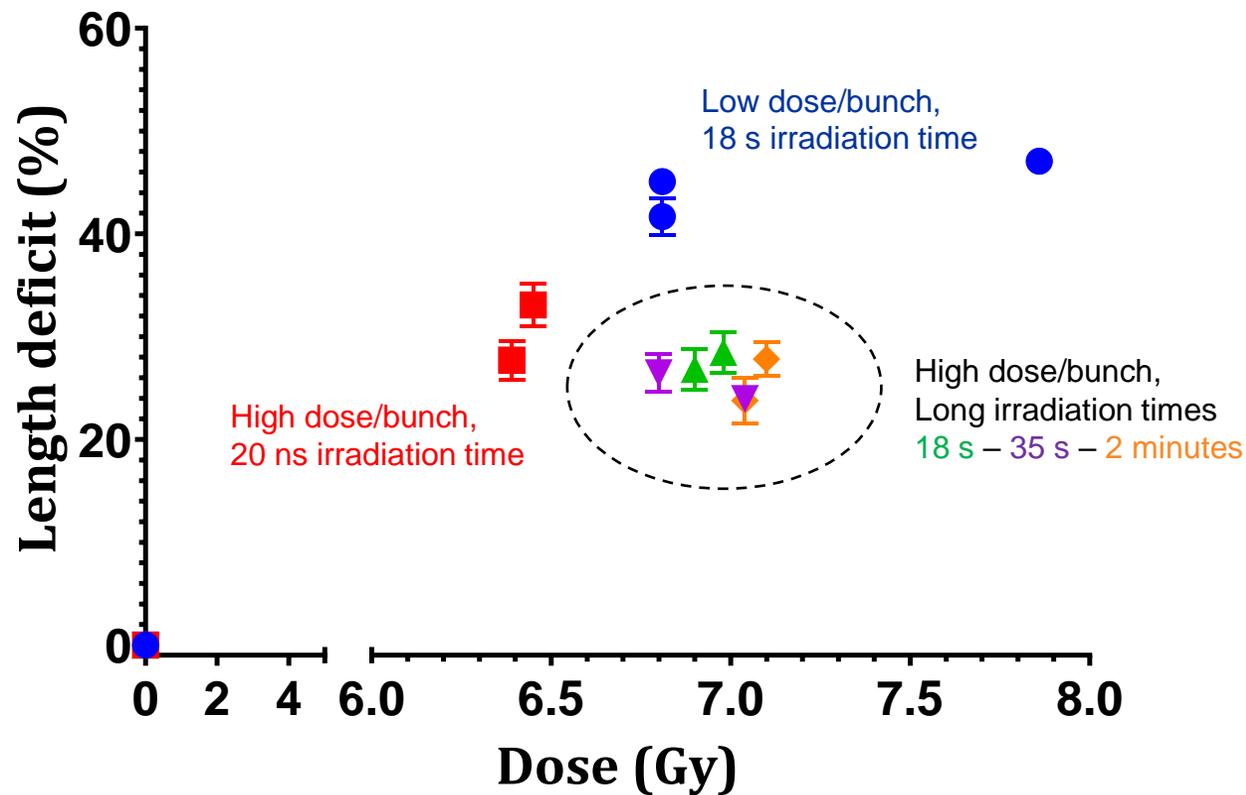
Same “instantaneous” dose rate



Factor ~ 15 in “instantaneous” dose rate



➔ What matters seems to be the dose rate over the bunch (ps time scale)



Preliminary results

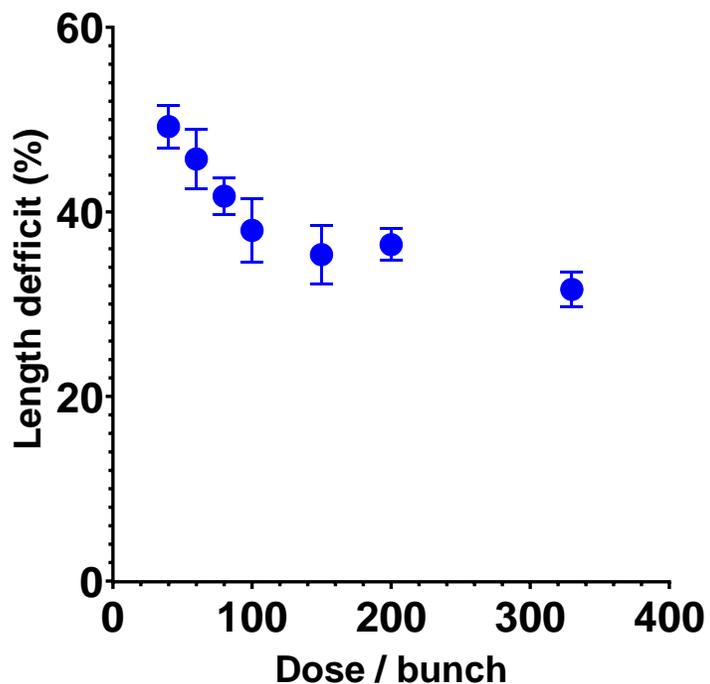


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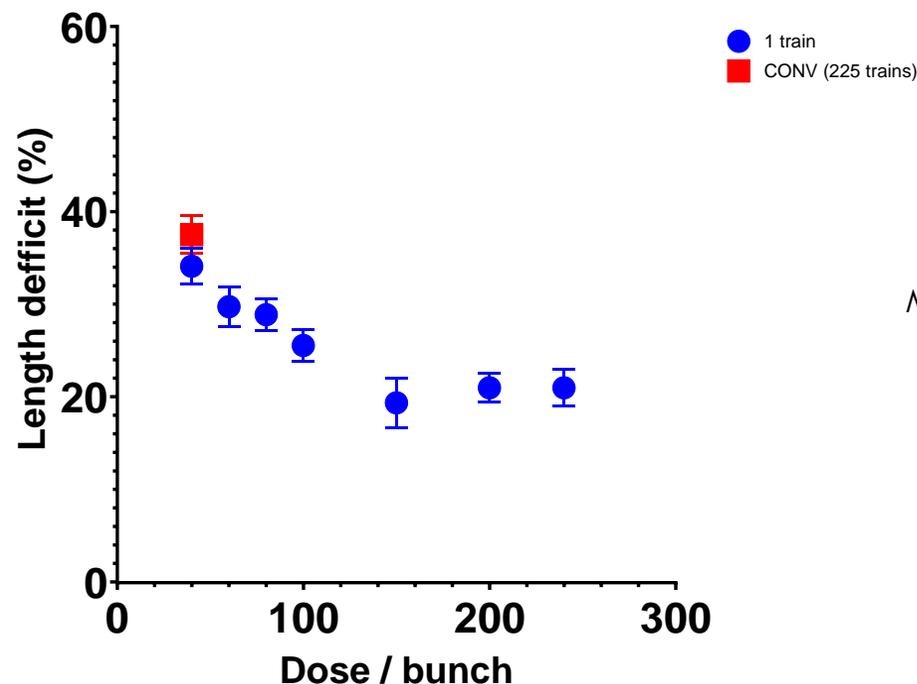
- CDR - (40mGy/bunch)
- 1 train (UHDR) - (240mGy/bunch)
- ▲ 0,625s (UHDR) - (240mGy/bunch)
- ▼ 1,2s (UHDR) - (240mGy/bunch)
- ◆ 4s (UHDR) - (240mGy/bunch)

See L. Kunz talk tomorrow

2025.07.03_CERN_Flat_ABWT_4hpf_9Gy_Dose bunch
escalation_1train_curve



2025.07.16_CERN_Flat_ABWT_4hpf_9Gy_Dose bunch
escalation_1train_curve



Preliminary results



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See L. Kunz talk tomorrow

“Recipe” for FLASH sparing:

- Dose > 10 Gy,
- Dose rate > 40 Gy/s (total irradiation time < 200 ms)

Two issues in my opinion seems critical for the potential clinical success of (VHEE)-FLASH:

SPACE

- Is it FLASH *local*?

i.e. is sparing maintained if *each portion* of the total irradiated area is treated within (say) 200 ms, or should the *total* irradiated area be covered within the 200 ms?

Is there a *minimum spot size* to be used when scanning?



Large field vs pencil beam scanning

VHEE vs hadrons

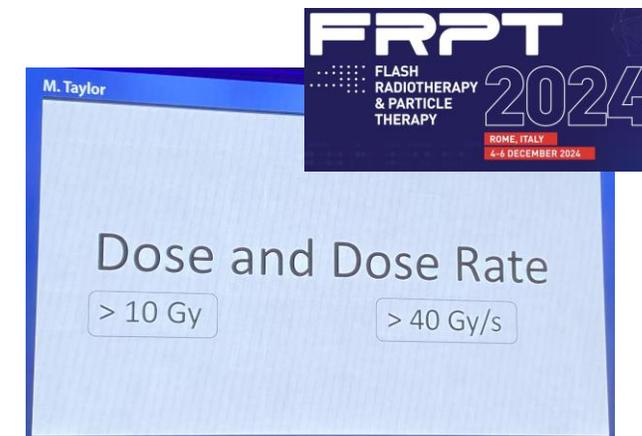
TIME

- Beams from accelerators have a very complex *time structure*. It's the simple “recipe” above valid in any case? Dose rate is sometimes an ambiguous definition, is the *average* or the *instantaneous dose rate* that matters? Or the dose rate over a *specific time scale*?



Maybe a road to:

- Easier machines
- More conformality



- The CLEAR facility provides since 2017 e- beams in the 60-200 MeV range with very flexible parameters to a variety of users
- The facility operation has been recently extended until end 2030. Several consolidation and upgrade activities are ongoing, in particular a new beamline, particularly suited for VHEE studies will become operational from 2026
- The CLEAR facility has developed flexible, intense beams and experimental techniques (beam shaping and handling, dosimetry...) adapted for VHEE/FLASH pre-clinical studies
- CERN is collaborating with a number of external user groups performing in multi-disciplinary activities in CLEAR, performing chemistry and biology studies (zebra fish eggs, cell cultures...) with VHEE beams
- Evidence of the importance of instantaneous dose rate (rather than average) and of the relevance of time scales faster than ~100 ms is emerging from recent experiments done in collaboration with HUG-UNIGE. This might be very important to:
 - Understand the FLASH mechanism
 - Allow for simpler, more compact and less costly VHEE/FLASH accelerator designs
 - Allow for high conformality in RT through multi-directional irradiation from a single accelerator

Thanks for your attention!

Acknowledgements to the CLEAR team:

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A. Aksoy, K. Sjobaek, L. Dyks, V. Rieker, J. Bateman, C. Robertson,
L. Wroe, E. Granados, M. Martinez, S. Curt, D. Gamba, ...*

and to our HUG-UNIGE collaborators: M-C. Vozenin, H. Kacem, J. Ollivier, L. Kunz ...

