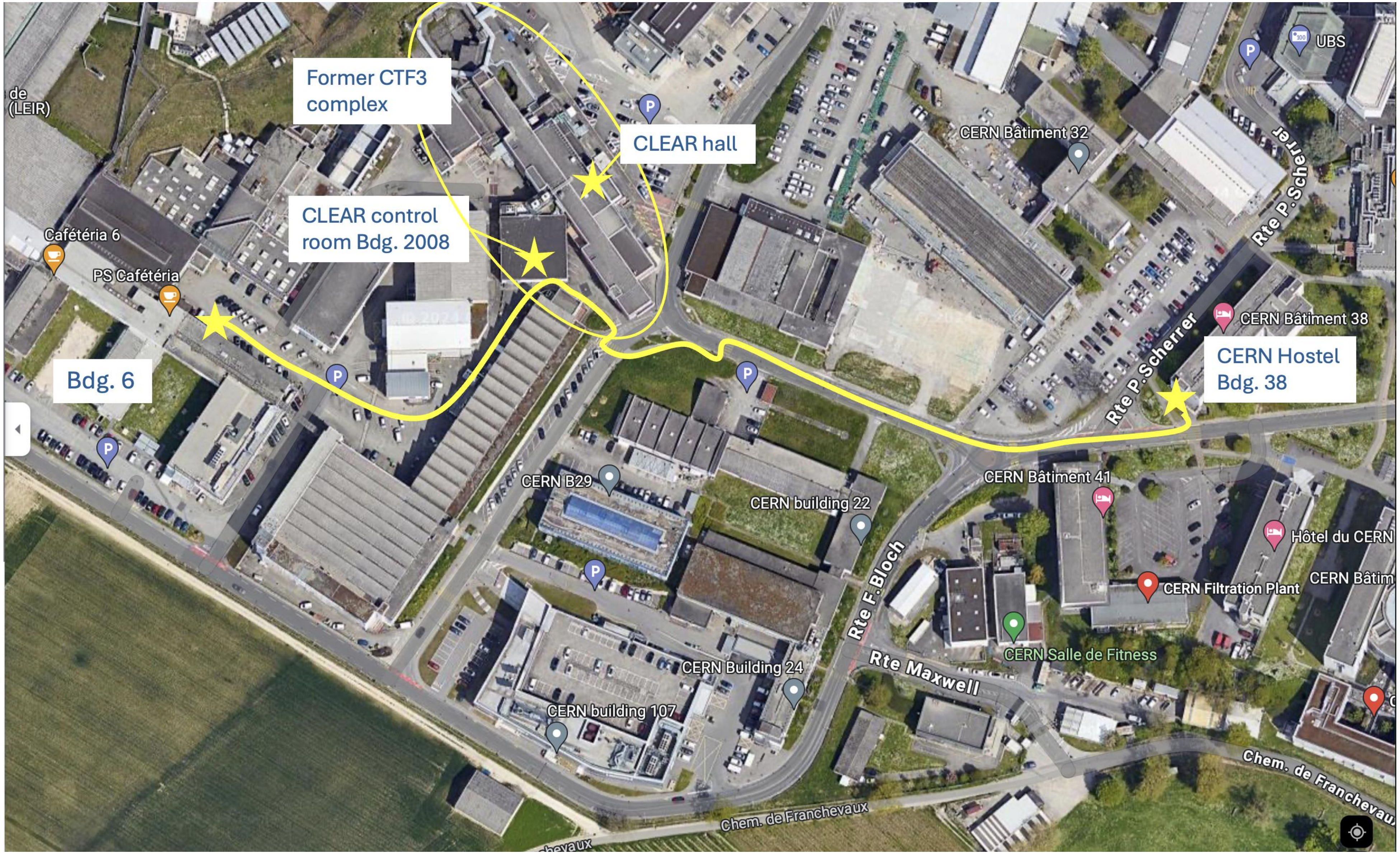
High-energy Electron Beams and the CLEAR Facility

EURO-LABS
EUROPEAN LABORATORIES FOR ACCELERATOR BASED SCIENCES

R. Corsini

for the CLEAR team

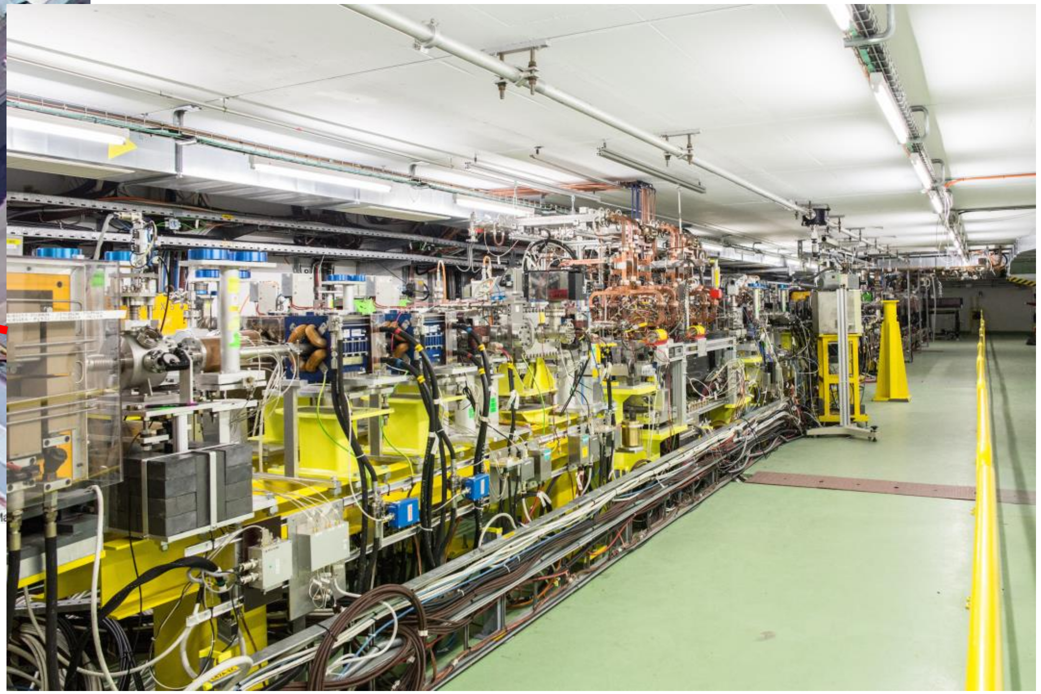
CLEAR location at CERN



From the CLIC Test Facility to CLEAR

CLIC Test Facility (CTF3) - completed its experimental program in 2016

Proposal to reuse the CLEX area and the CALIFES e- linac for accelerator R&D



CLEAR is a user facility at CERN, running in parallel with the main CERN accelerator complex, with the primary goal of enhancing and complementing the existing accelerator R&D and testing capabilities at CERN

Approved December 2016

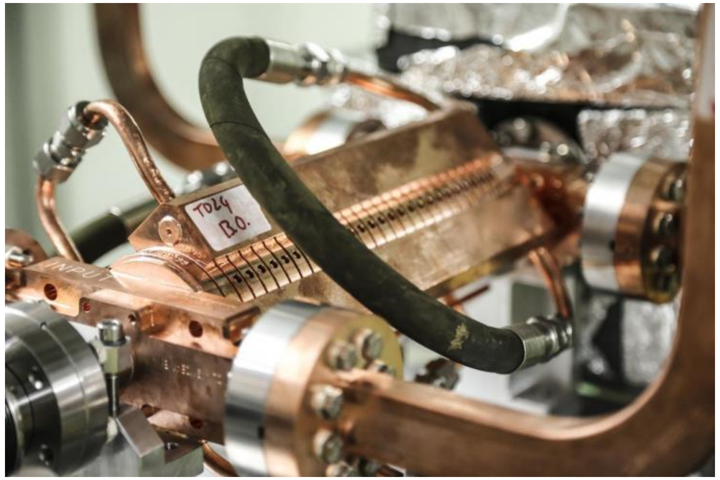
High-energy electron beams?

A clarification about the title:

- CLEAR can provide electron beams up to an energy of 220 MeV
- This is higher than energies used in medical linacs (ranging from a few MeVs to ~ 25 MeV)
- Electrons above 100 MeV are thus called Very High Energy Electrons (VHEE) in the field of radiotherapy

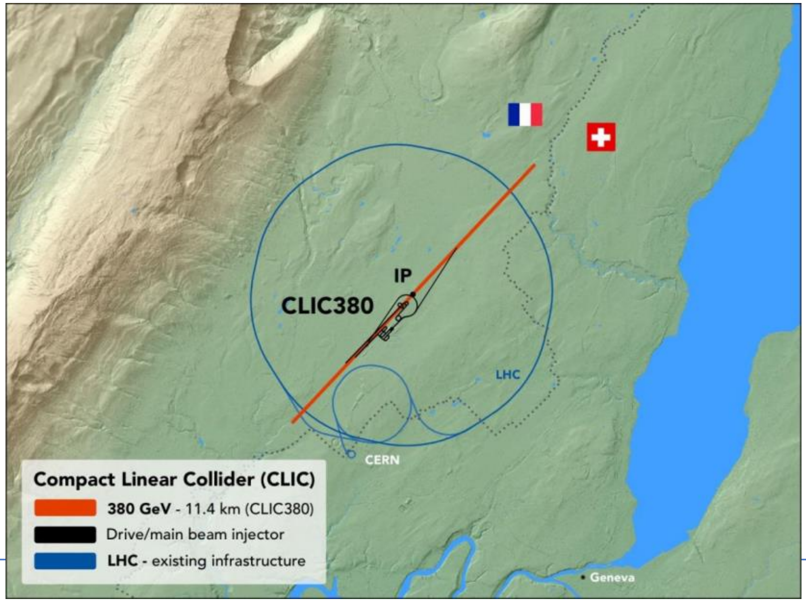
Electrons from CLEAR are not considered especially high-energy at CERN

- The precursor of LHC, called LEP, which occupied the same tunnel, collided electron and positron beams of up to 100 GeV
- The CLIC project, whose test facility CTF3 originated CLEAR, is a proposal for an $e^+ e^-$ linear collider with beams up to 1.5 TeV

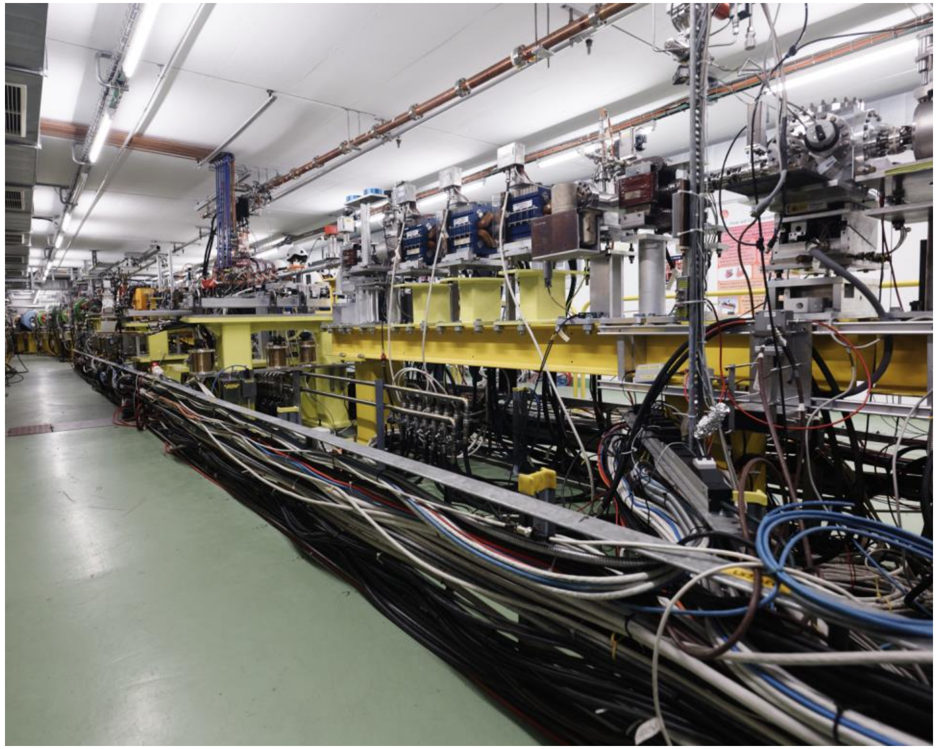


CLIC accelerating structures demonstrated in CTF3 gradients in excess of 100 MV/m

The footprint of the first stage of the CLIC project, reaching 190 GeV per each of the two beams (e^+ and e^-) in 11.4 km



The CERN Linear Electron Accelerator for Research (CLEAR)

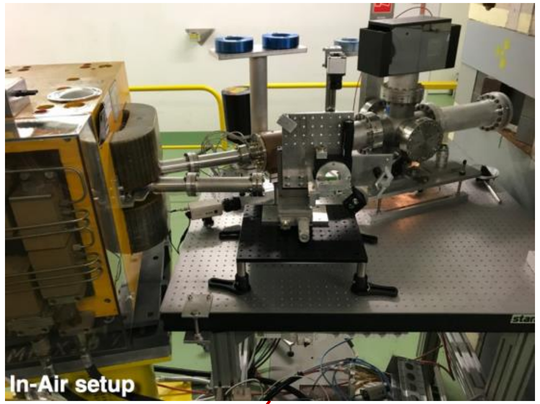


CLEAR is a versatile 200 MeV electron linac + a 20 m experimental beamline, operated at CERN as a multi-purpose user facility.

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. for testing electronic components in collaboration with ESA or for medical purposes(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.

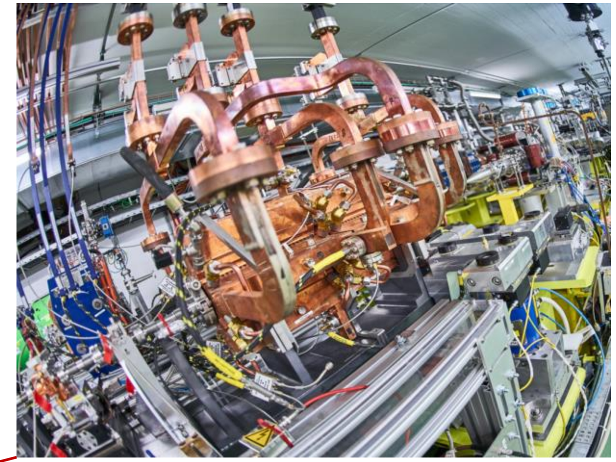
CLEAR provides electron beams for a large and varied range of experiments.



In-air test stand

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

Irradiation for medical and other applications

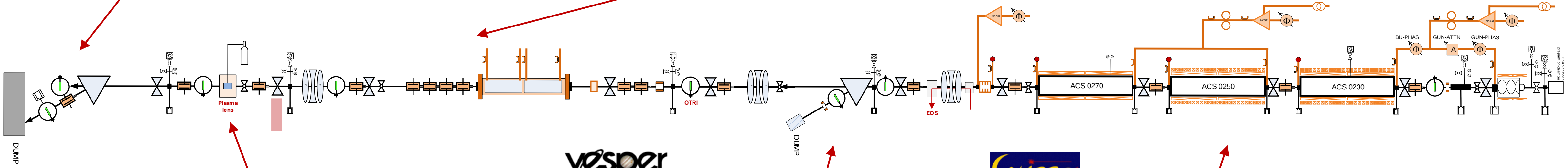


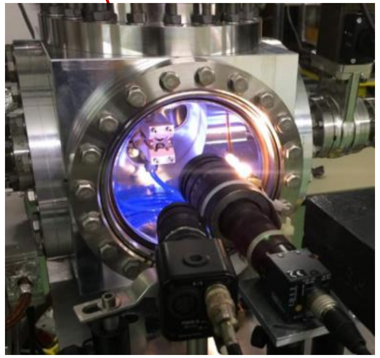
CLIC Test-Stand

High-gradient and linear collider R&D

+ *Beam instrumentation area*

CERN Linear Electron Accelerator for Research

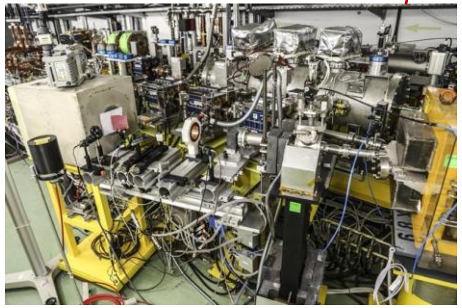




The Plasma Lens Experiment

Novel concepts of plasma-based focusing and acceleration

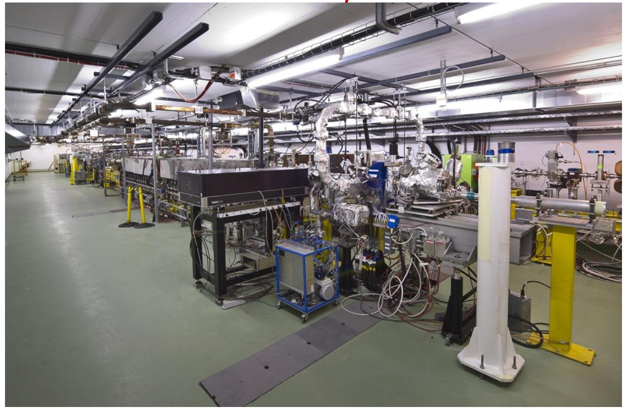
vesper



VESPER

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

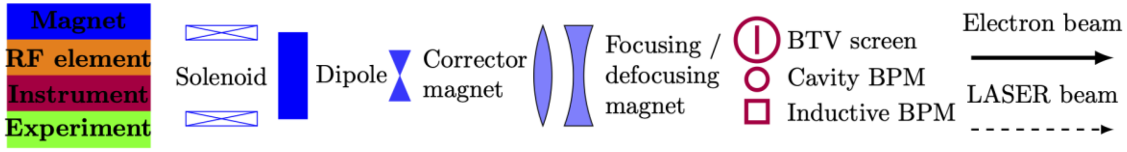
CALIFES

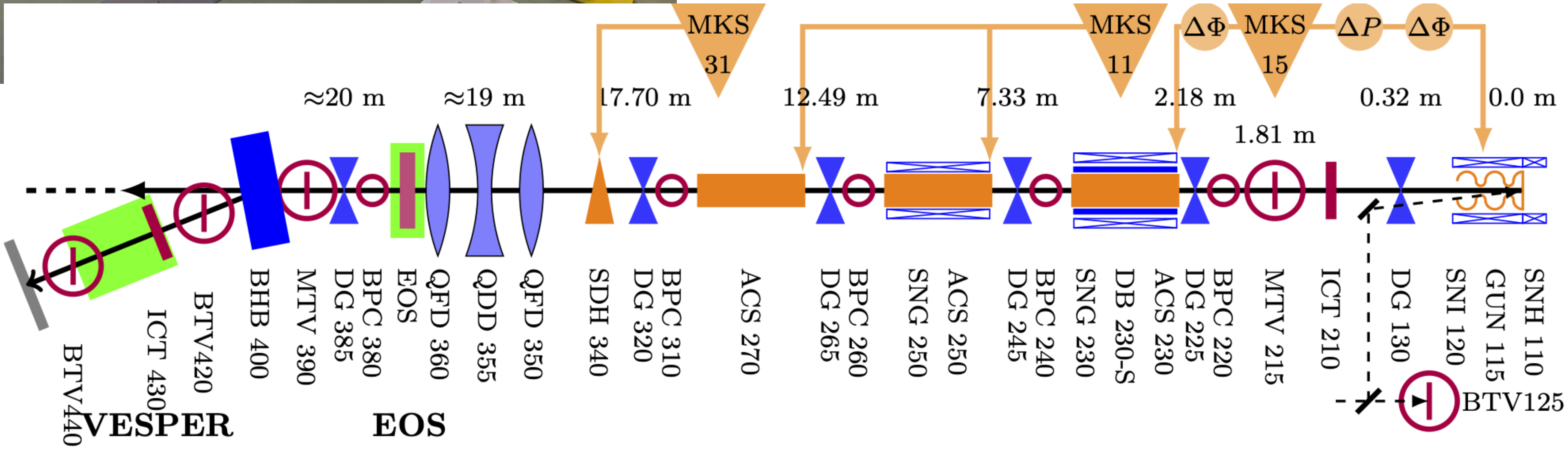


CALIFES electron linac

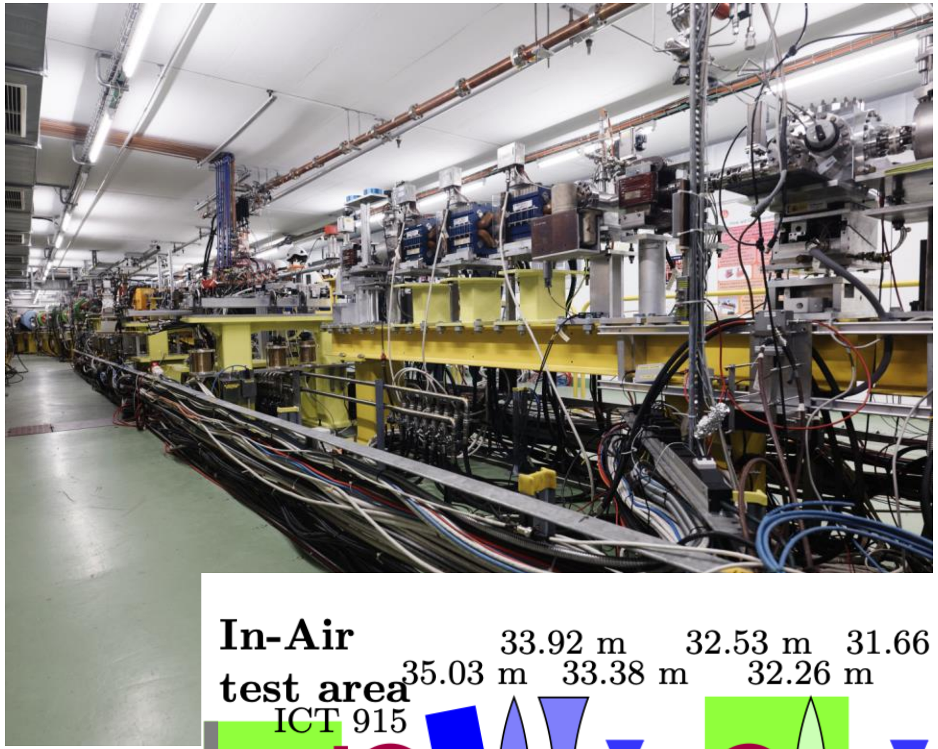
Flexible accelerator providing 200 MeV electron beams to all CLEAR users clear

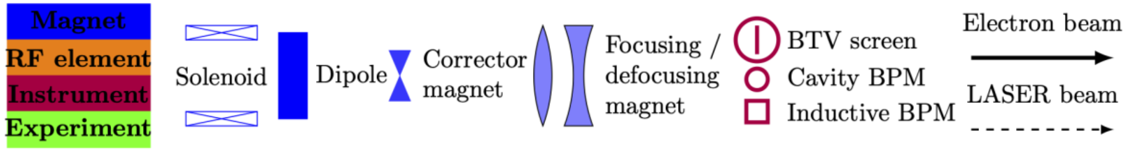
The linac (and the VESPER spectrometer)

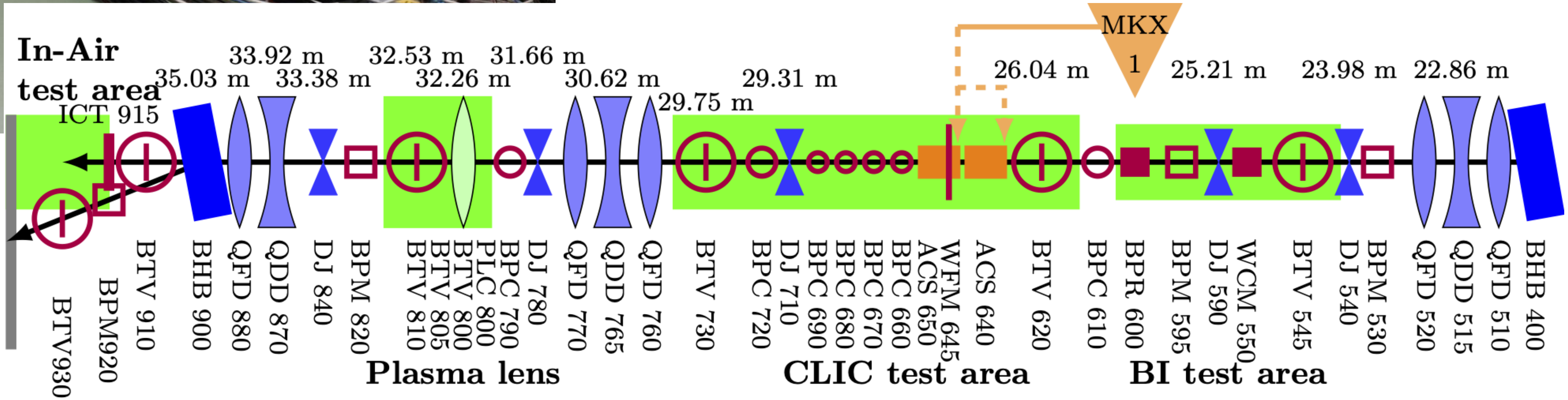




The experimental beam line





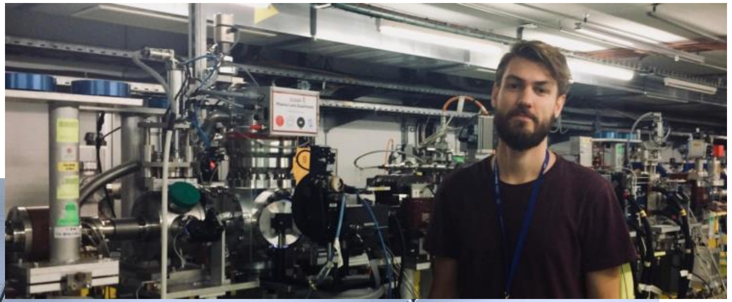


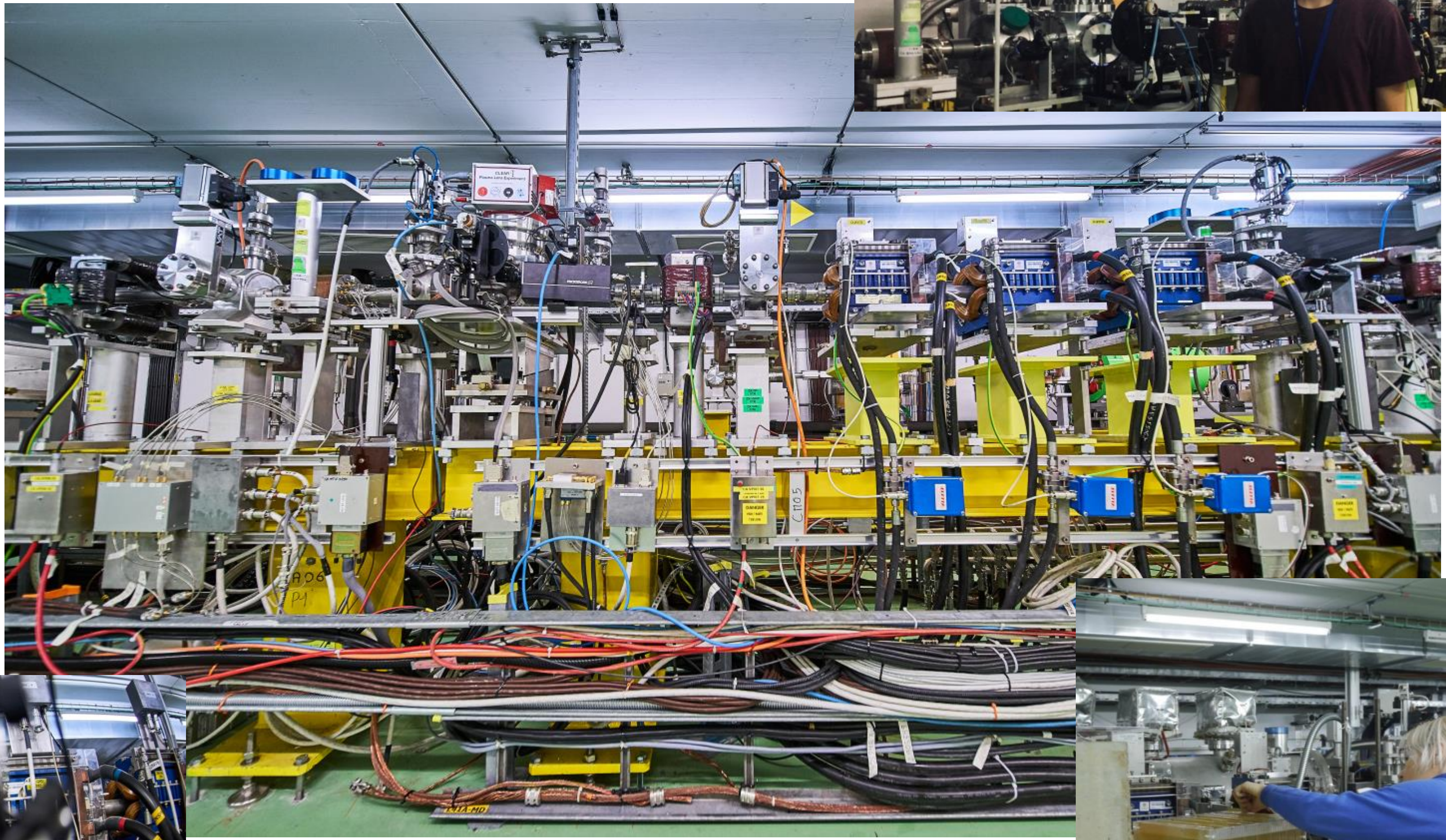
CLEAR Operation 2017 - 2023

Start with beam August 2017

- 19 weeks of operation in 2017
- 36 weeks in 2018
- 38 weeks in 2019
- 34 weeks in 2020
- 35 weeks in 2021
- 37 weeks in 2022
- 38 weeks in 2023

Due to Covid-19 related measures, 2020-2021 activities were impacted, and mainly limited to CERN users





Operation

- CLEAR is a stand-alone installation, thus operation during general stops of the global CERN accelerator complex, including long shut-downs, is possible.

- CLEAR is operated for 30 to 40 weeks/year – typically from March to December, often 2-3 weeks stop in summer.
  - Operation organized over 2 shifts, roughly during working hours, 5 days/week
  - No night shifts or week-end running (apart few exceptions)
  - Sometimes remotely supervised operation in nights/week-ends (low-charge irradiation – none recently)

- Current operating team:
  1 Staff, 1 ½ associates, 2 fellows, 1 PhD student, plus 1 part-time associate (in remote)

- Support from CERN services and groups on technical systems, in general on best effort basis and subject to priorities

- Detailed weekly activities organized at the Monday operation meeting (often followed by access in the hall) and coordinated by a weekly supervisor (member of the operation team)

CLEAR Users (2023)

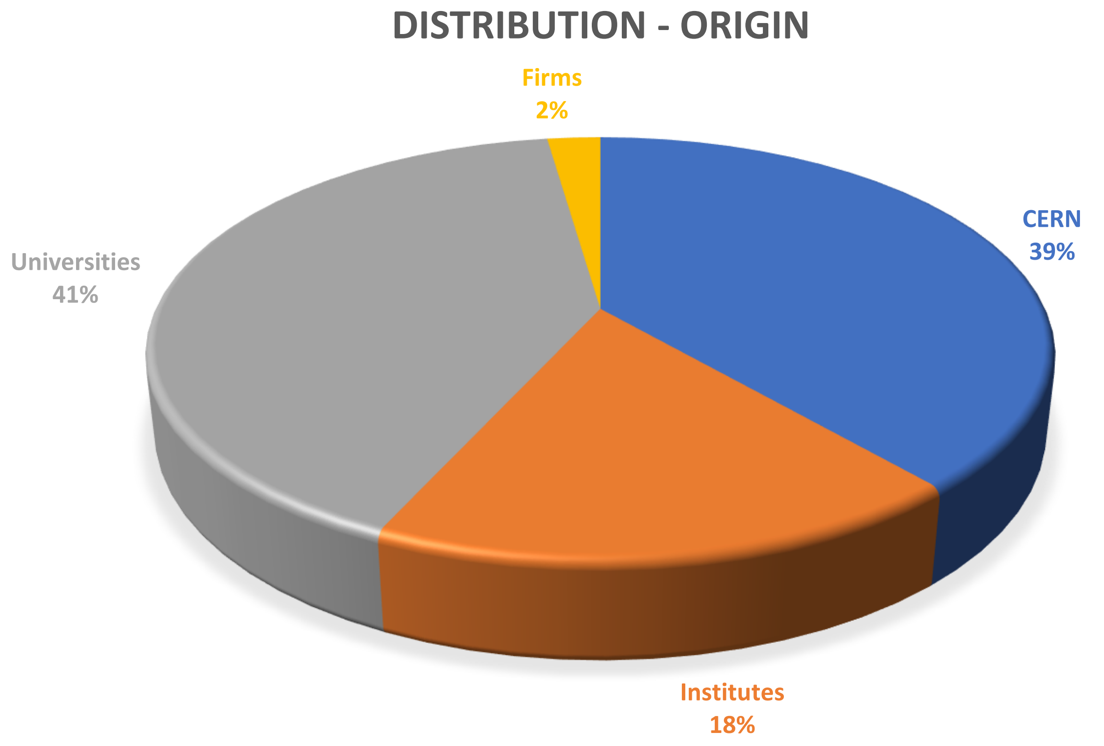
- 27 independent experiments (~ 35 including repetitions, plus MDs)
- About 21 User Groups internal/external
- More than 18 external collaborating institutes

CERN – ABP
CERN – BI
CERN – RP
CERN – EP
CERN – TE
CERN – SY

BERGOZ

Manchester U.
Oxford U.
RHUL
London U.
Liverpool U.
Strathclyde U.
Oslo U.
Victoria U.
Kansas U.
Politecnico Milano

PSI
CHUV
EPFL
INFN Bologna
INFN Padova
KIT
Cockcroft Inst.
JAI



W. Farabolini

Activities (2023)

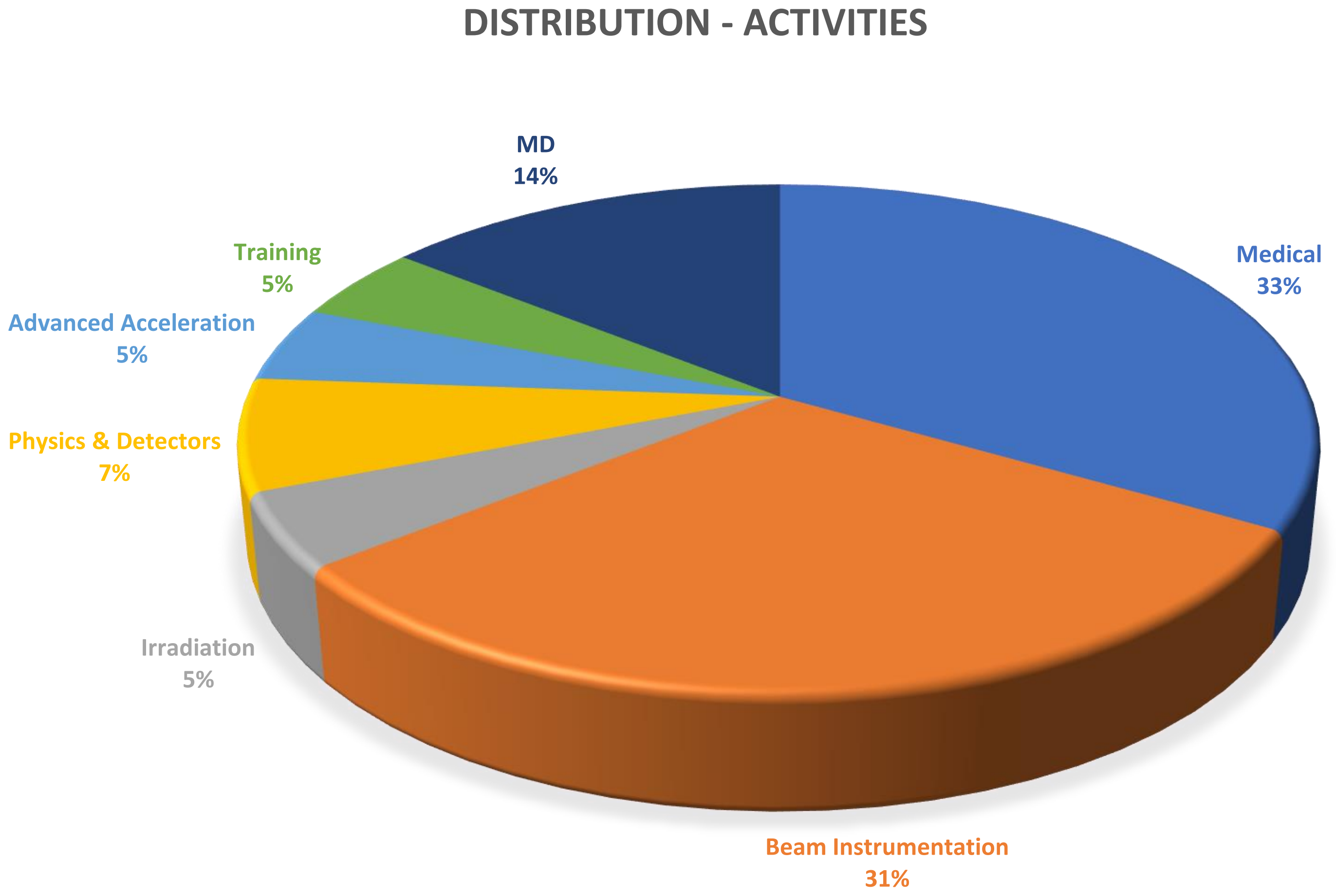
Two main activities at present:

- medical
- beam instrumentation R&D

Together they constitute about 2/3 of the total requests/beam time

Other activities are as important, they just take less time, or have less interested user groups

In the following,
I'll give some highlights on all our activities and on the experimental results obtained



W. Farabolini

CLEAR operation peculiarities

- Flexibility:
  - flexibility of access (small radioactive activation, fast access to the accelerator),
  - flexibility in acceptance and scheduling of experiments,
  - flexibility in beam conditions (from low charge single-bunch to trains of high charge bunches, beam sizes from a few tens of microns to cm size, different energies and bunch lengths…),
  - flexibility in adapting hardware and experimental set-ups to evolving user requirements,
  - flexibility in experiment locations (in-air and in vacuum),
  - flexibility (not to be abused) in working after hours and week-ends
- Availability: long experimental run (March-December), run during long shut-downs.
- Support: the CLEAR team provides to the users specialized equipment, support for machining of small parts, assembly of experimental set-ups, small vacuum interventions, data acquisition, data analysis…
- Collaboration: CLEAR is a user facility but in most cases, we don't just provide a beam following user specs, but we help - if needed - to better define the experiment, optimize methods and adapt the measurement program, analyze and interpret the results. Many of the CLEAR experiments evolve in a full two (or more) sided collaboration.
- Flexibility. Did I mention flexibility?

Publications – scientific output

In 6 ½ years of operation, the experimental activities carried out in the CLEAR user facility have generated:

- 23 Journal papers
- 36 Conference papers
- More than 12 completed PhD thesis, plus several ongoing.
- More than 17 outreach publications in specialized journals, press releases, …

https://clear.cern/content/publications

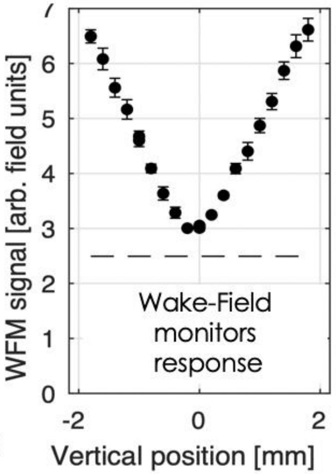
Journal papers:

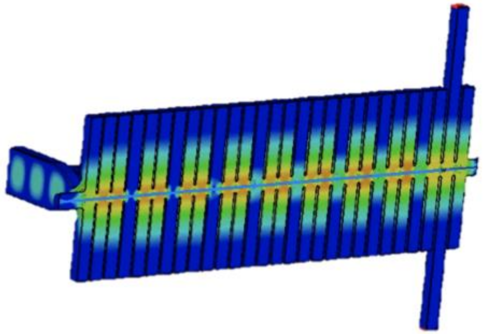
- **Nature Scientific Reports - May. 2024**: CERN-based experiments and Monte-Carlo studies on focused dose delivery with very high energy electron (VHEE) beams for radiotherapy applications (doi).
- **Physics in Medicine & Biology - Apr. 2024**: Development of a novel fibre optic beam profile and dose monitor for very high energy electron radiotherapy at ultrahigh dose rates (doi).
- **Physics Medicine & Biology - Feb. 2024**: Mini-GRID radiotherapy on the CLEAR very-high-energy electron beamline: collimator optimization, film dosimetry, and Monte Carlo simulations. (doi).
- **IEEE Sensors Journal - Jan. 2024:** Plastic scintillator dosimetry of ultrahigh dose-rate 200 MeV electrons at CLEAR (doi).
- **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 (doi).
- **Physical Review Accelerators and Beams - Dec. 2021:** Strong focusing gradient in a linear active plasma lens (doi).
- **Biomed. Phys. Eng. Express - Dec. 2021**: VHEE beam dosimetry at CERN Linear Electron Accelerator for Research under ultra-high dose rate conditions (doi).
- **IEEE Transactions on Nuclear Science - Mar. 2021:** Electron-Induced Upsets and Stuck Bits in SDRAMs in the Jovian Environment (doi).
- **Physics Letters A - Mar. 2021**: Diffractive shadowing of coherent polarization radiation (doi).
- **Nature Communications Physics - Feb. 2021:** An experimental study of focused very high energy electron beams for radiotherapy (doi).
- **Nature Scientific Reports - Feb. 2021**: Evaluating very high energy electron RBE from nanodosimetric pBR322 plasmid DNA damage (doi).
- **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 (doi).
- **IEEE Transactions on Instrumentation and Measurement**: A Measurement Method based on RF Deflector for Particle Bunch Longitudinal Parameters in Linear Accelerators (doi).
- **Nature Scientific Reports - Jun. 2020**: The challenge of ionisation chamber dosimetry in ultra-short pulsed high dose-rate Very High Energy Electron beams (doi).
- **Nature Scientific Reports - May 2020**: Enhancing particle bunch-length measurements based on Radio Frequency Deflector by the use of focusing elements (doi).
- **Physical Review Accelerators and Beams - Feb. 2020**: Noninvasive bunch length measurements exploiting Cherenkov diffraction radiation (doi).
- **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:** A beam-based (sub-)THz source at the CERN Linear Electron Accelerator for Research facility (doi).
- **IEEE Transactions on Nuclear Science - Jan. 2019:** Mechanisms of Electron-Induced Single-Event Latchup (doi).
- **Physical Review Letter - Nov. 2018**: Emittance Preservation in an Aberration-Free Active Plasma Lens (doi).
- **Nuclear Instruments and Methods in Physics Research Section A - Nov. 2018**: Overview of the CLEAR plasma lens experiment (doi).
- **IEEE - Jun. 2017:** High-Energy Electron-Induced SEUs and Jovian Environment Impact (doi).

CLIC and high-gradient acceleration

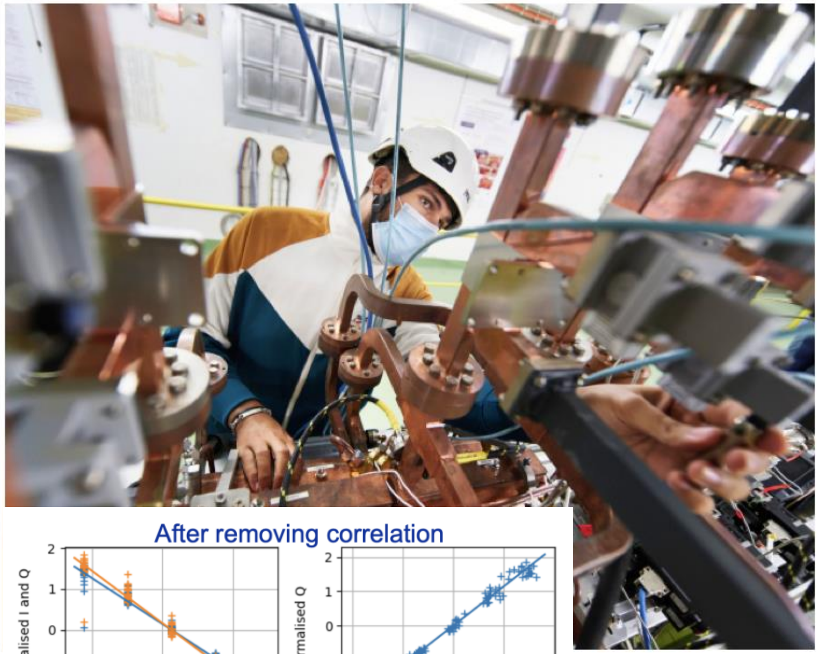
Key CLIC related activities

Experiments:
- Wake-Field monitors
- Wake-field kicks
- CLIC cavity BPMs





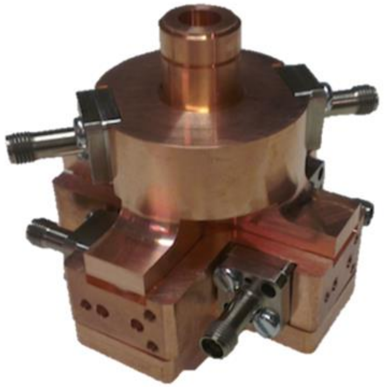
A. Gilardi, K. Sjobaek, M. Wendt, A. Lyapin

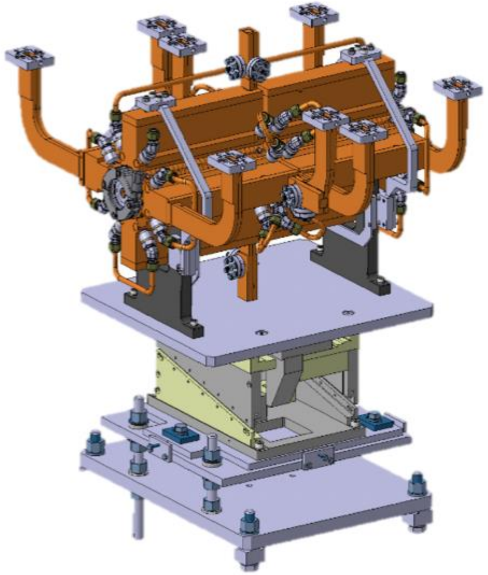


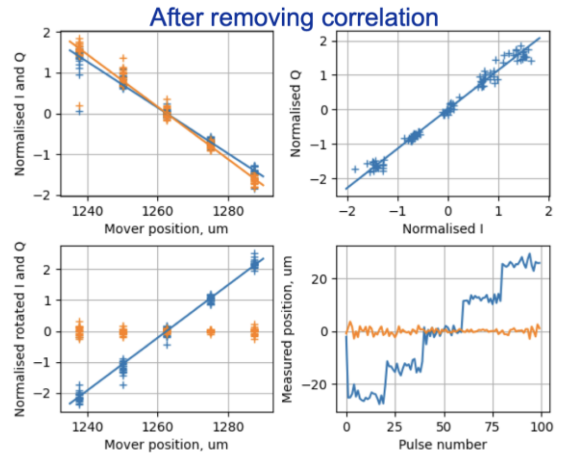
Main collaborators
- University of Oslo
- CEA - Saclay
- Università di Napoli Federico
- RHUL

Future step, connecting the cavity to X-Box1

possible tests:
- RF kicks
- Breakdown kicks
- RF effect on WFMs
- Stability & reliability runs

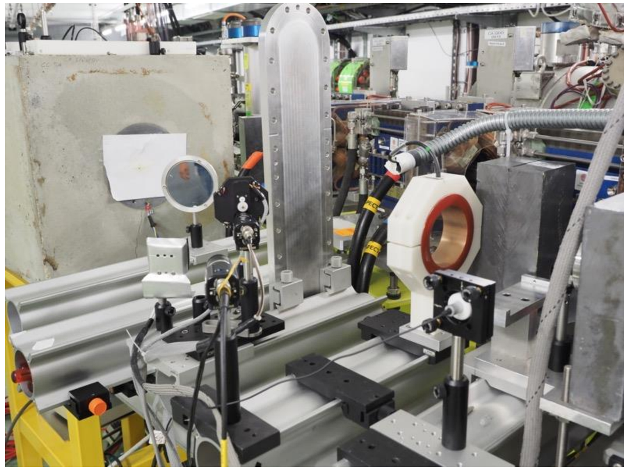


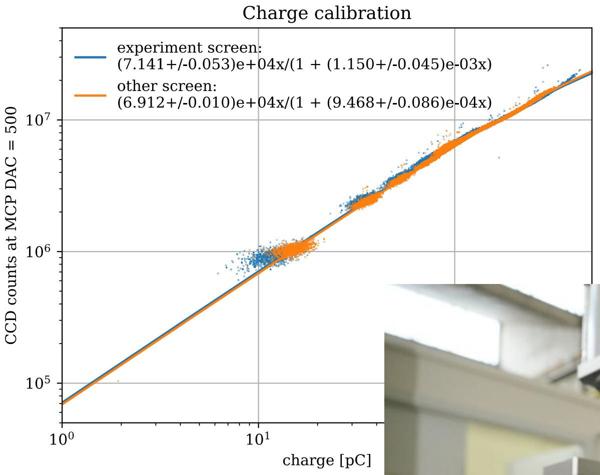




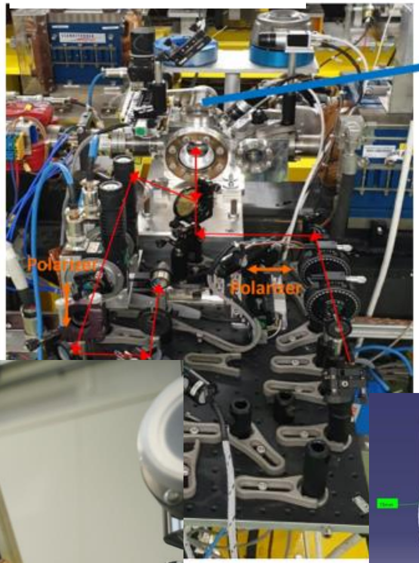
Another CERN client - AWAKE

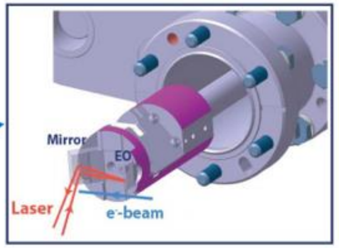
Charge calibration measurements of the AWAKE spectrometer scintillating screen/camera combination performed in 2017, 2018, 2019





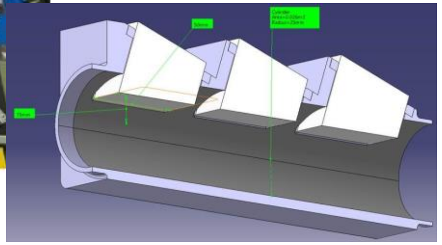
E. Gschwendtner

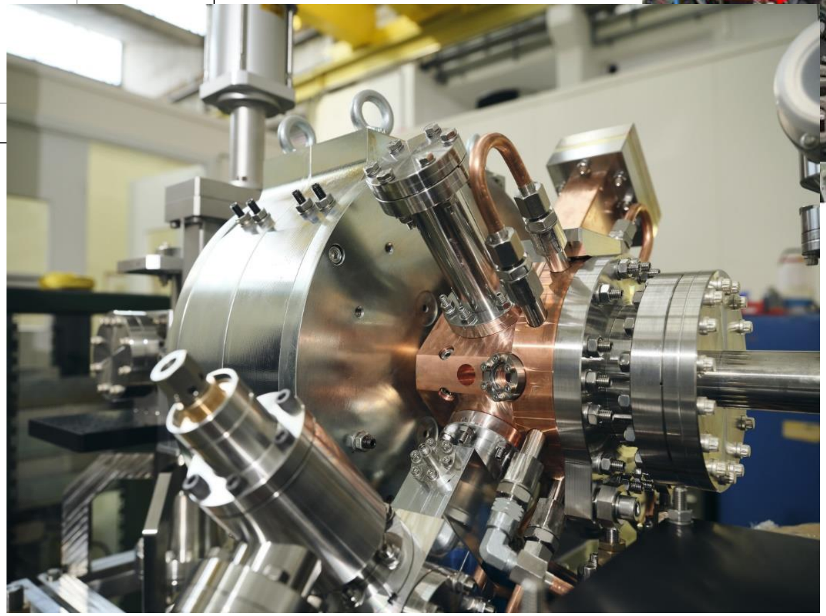




Bunch length monitors:

EOS and ChhDR





Common development of novel electron source

CLIC-AWAKE-CLEAR

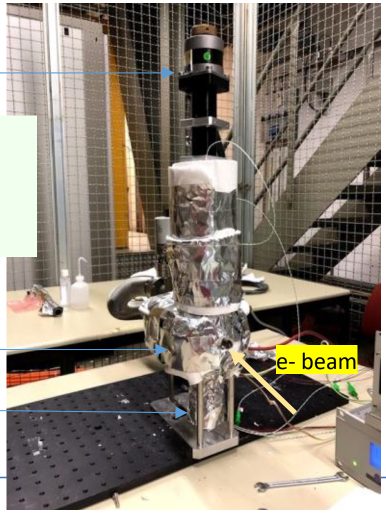
Cherenkov BPMs

Beam Screen Survival Tests in Rubidium

Screen actuator

Sapphire viewports

Rb reservoir (empty)

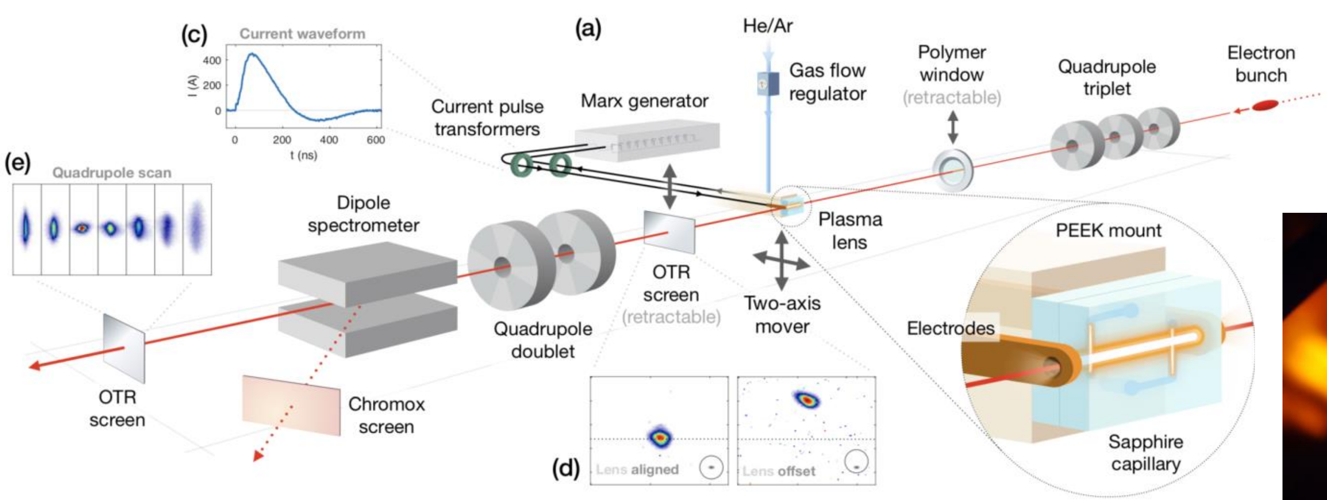


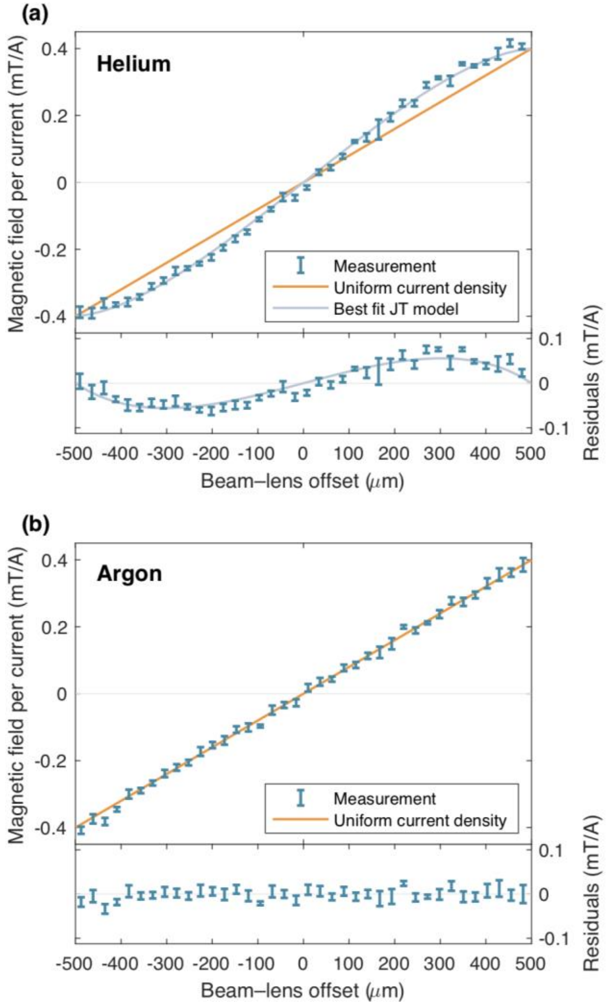
The Plasma lens experiment

Lead by Univ. of Oslo, in collaboration with CERN, Desy and Oxford Univ.

Emittance Preservation in an Aberration-Free Active Plasma Lens

C. A. Lindstrøm, E. Adli, G. Boyle, R. Corsini, A. E. Dyson, W. Farabolini, S. M. Hooker, M. Meisel, J. Osterhoff, J.-H. Röckemann, L. Schaper, and K. N. Sjobak
Phys. Rev. Lett. **121**, 194801 – Published 7 November 2018



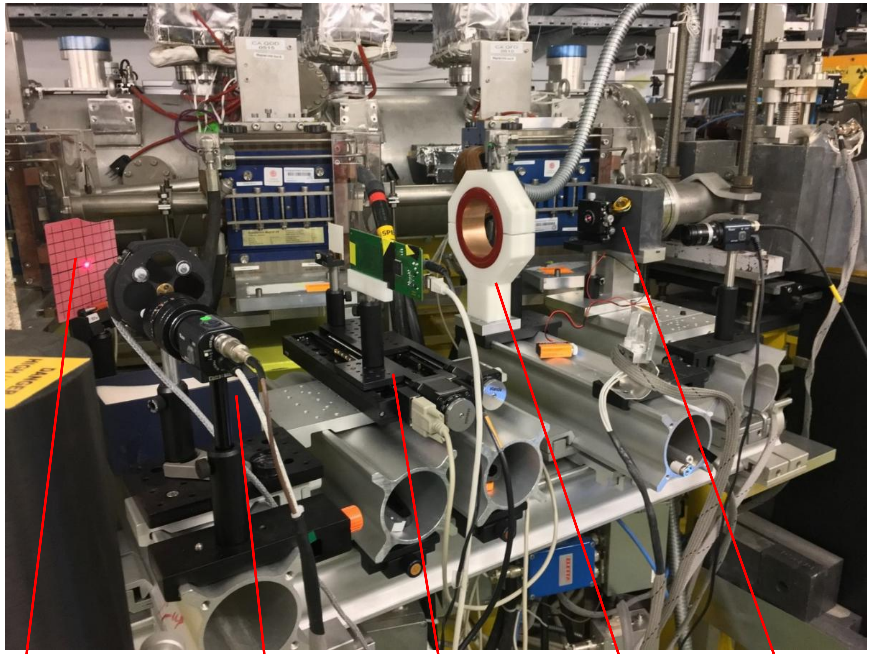


- Emittance preservation in an active plasma lens demonstrated for the first time with the use of an argon-based discharge capillary.
- Direc… d nonlin… .

October 2019 – record magnetic field gradient of 5.2 kT/m !

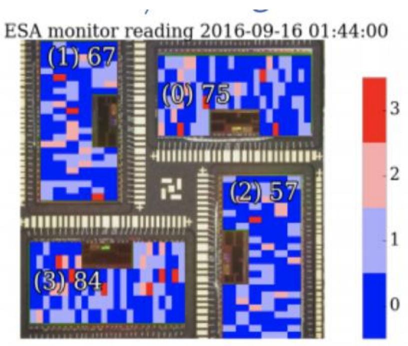
- Quadrupole scans demonstrated expected emittance preservation and growth (respectively) consistent with the measured field profiles.

vesper irradiation facility



alignment screen | camera | movable stage | charge monitor | collimators

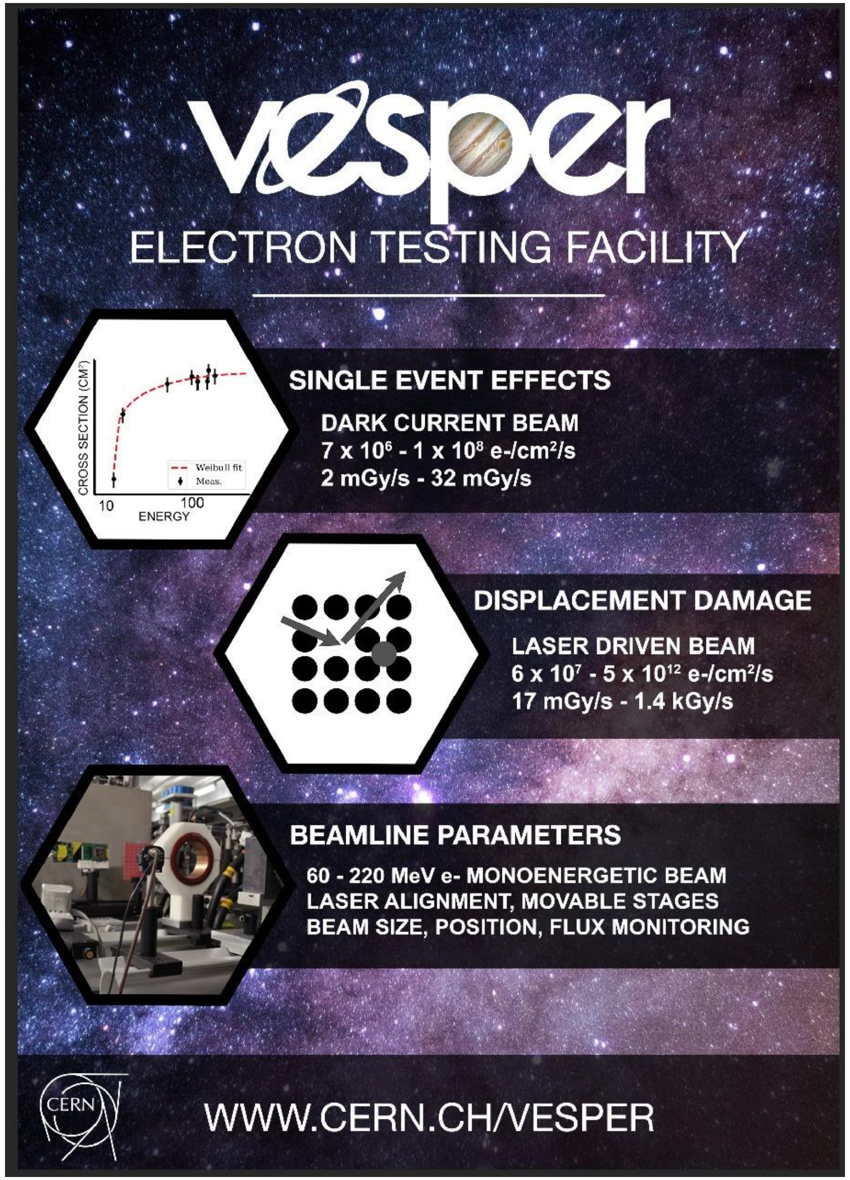
- Installed in a spectrometer line
- In air
- Fully equipped
- Large, homogeneus beam



Radiation hardness of electronic components for space missions

JUICE mission (ESA)

R. Garcia Alia



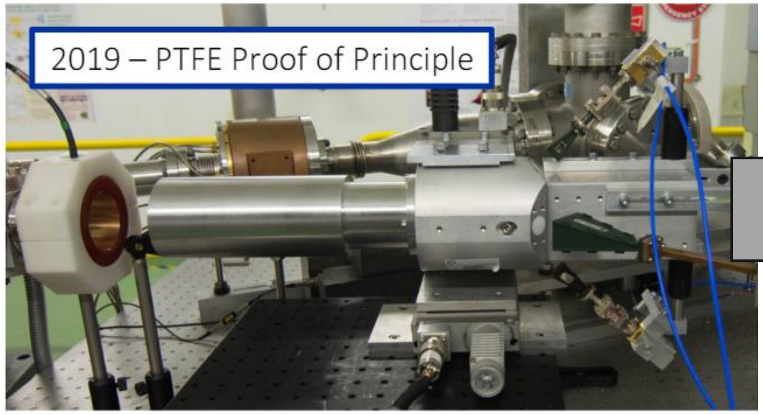
Beam Instrumentation activities

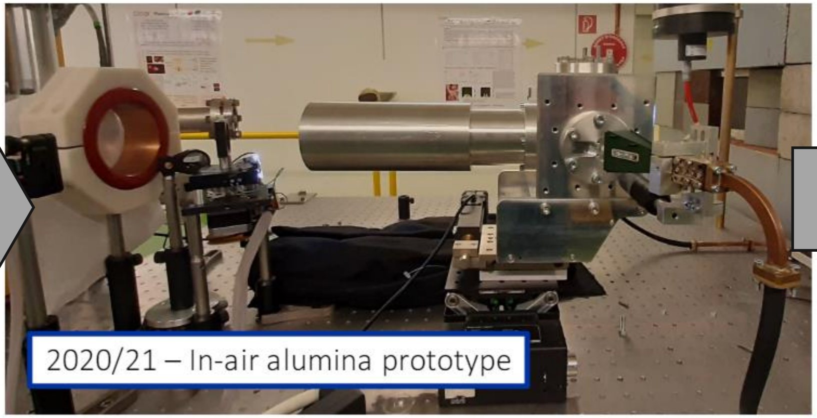
R&D programmes

S. Mazzoni

- Availability of CLEAR allows to develop a long-standing, coherent programme in topics such as diffracted radiation emission, electro optical encoding techniques, optical BLMs
- Example: development of a beam position monitor based on diffracted Cherenkov Radiation from prototyping (2019) to (almost) operational instrument installed in AWAKE in 2022/23…via 3 PhDs!

E. Senes et al. Selective electron beam sensing through coherent Cherenkov diffraction radiation, accepted for publication in Phys. Rev. Research 2024

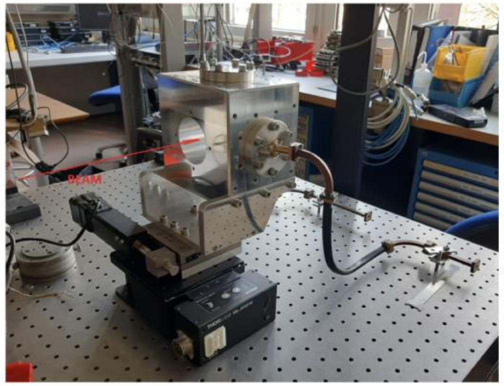




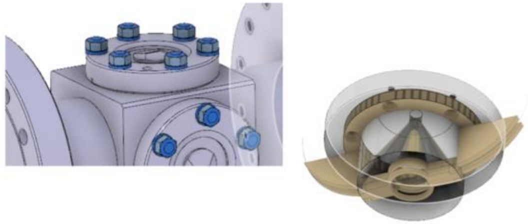
Beam Instrumentation activities – some examples

S. Mazzoni

- **Longitudinal profile ChDR / EO tests**
  - Test of vacuum ChDR pickups for longitudinal profile measurement with ns / tens of ps resolution
  - Detection scheme using 20 – 40 GHz electro-optical modulators and 780/1550 nm laser at CLEAR. Other EM probes to test
  - Proof of principle at CLEAR, then tests in HRM. Long term study for FCC



- **Test of LHC EO buttons** (CERN/RHUL)
  - Beam validation of a technology being developed in collaboration with RHUL for HL-LHC
  - Using fiber-coupled electro-optical waveguide coupled to a 50 Ohms terminated electrostatic button



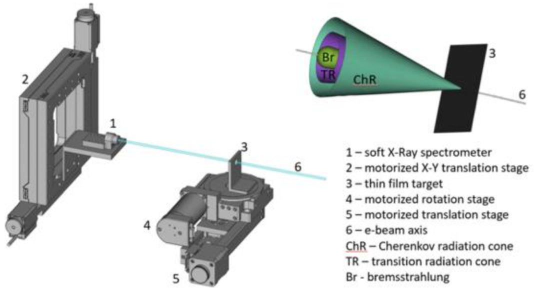
Recent Publications

- A. Curcio et al, "Diffractive shadowing of coherent polarization radiation", Phys. Lett. A **391**, 127135 (2021)
- A. Curcio et al, "Noninvasive bunch length measurements exploiting Cherenkov diffraction radiation", PRAB **23** (2020)
- A. Curcio et al. "Beam-based sub-THz source at the CERN linac electron accelerator for research facility", PRAB **22** (2019)
- R. Kieffer et al, "Experimental Observation of "Shadowing" in Optical Transition Radiation", Phys. Rev. Lett. **120** (2018)
- Yearly reporting to conferences (IBIC, IPAC, LCWS, …)

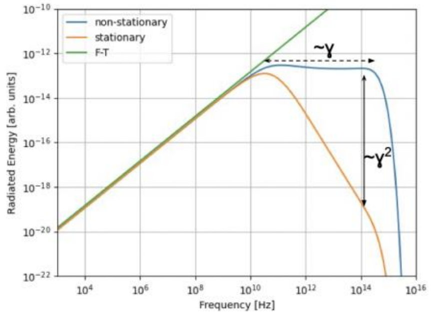
- **Optical BLM tests** (CERN)
  - Test of new optical BLM. Loss signal: Cherenkov Radiation produced in fibres.
  - 2020: measurement of ChR as a function of angle to benchmark simulations
  - 2021: improved read-out electronics and new sensors (SiPM, PMT, PD) test with low intensity bunches / trains
  - Complement to BL tests in SPS

R&D

- **X-ray Cherenkov test** (Belgorod)
  - Study of ChR in soft X-rays regime.
  - Absolute light yield and angular distribution as a function target angle
  - Preparation affected by COVID. Foreseen 2nd half of 2021



- **Validation of ChDR theoretical model** (CERN)
  - Models for ChDR still not fully validated. Basic tests to measure ChDR spectrum in the range 100-300 GHz
  - Verification needed for applications to high energy beams (FCC)
  - Radiation produced by dielectric conical target, tests in Summer 2021

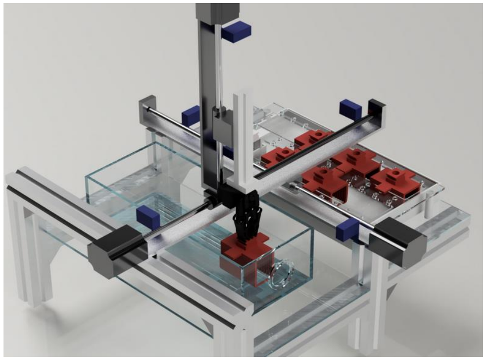
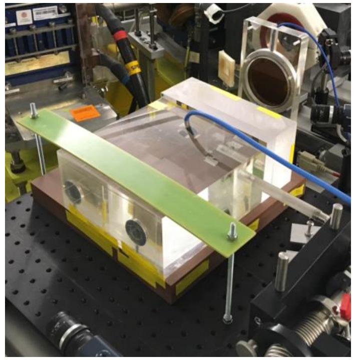


Medical Applications

The potential use of very high-energy electron (VHEE) beams (50-250 MeV) for Radio Therapy (RT) recently gained interest, since electrons at these energies can travel deep into the patient.

- Potential advantages of VHEE RT:
  - Depth – dose profile for electrons better than X-rays
  - Charged particles can be focused and steered (not possible with X-rays)
  - Electron beams rather unsensitive to tissue inhomogeneities
  - Electron accelerators comparatively more compact, simpler and cheaper than proton/ion machines
- This last advantage is now even more true given the recent advancements on high-gradient acceleration (CLIC technology)
- Ultra-high dose rate (above 100 Gy/s) radiation delivery (FLASH), showed normal tissue sparing, without compromising tumor control. Electron linacs can relatively easily reach the high beam currents needed for FLASH treatment of large fields.

More and more existing electron linac facilities are now being intensively used to investigate VHEE/FLASH RT

VHEE/FLASH RT studies at the CLEAR facility (CERN)

Facility	Applications
ARES	Accel. components, Diagnostics R&D Medical: VHEE RT, Electron CT Acceleration: ACHIP [29]
CLARA	Accel. components, Diagnostics R&D Medical: VHEE RT Acceleration: DWA, (P/L)WFA, THz
CLEAR	High gradient acceleration, plasma lens Radiation damage, Diagnostics R&D Medical: VHEE & FLASH RT
FLUTE	Diagnostics R&D, THz Experiments Medical: FLASH RT, Detectors Machine Learning
PITZ	Min. beam emittance developments THz source development Medical: FLASH RT & dosimetry
SPARC_LAB	Acceleration: PWFA, LWFA Radiation sources: FEL, THz, betatron

From: D. Angal-Kalinin et al., Electron beam test facilities for novel applications, Proc. IPAC '23

The FLASH effect

- FLASH is a biological effect, in which Ultra High Dose Rate (UHDR) radiation delivery destroys cancerous cells while sparing healthy surrounding tissues.
- Observed for the first time in 2014: mice tumours were irradiated with short pulses (≤500 ms) at Ultra High Dose Rate (≥40 Gy/s).
- The FLASH effect has been seen with protons, gamma and low energy electrons.
- Very High Energy Electrons (VHEE) would be used to treat deep seated tumours.
- The FLASH effect is extensively studied including in CLEAR.

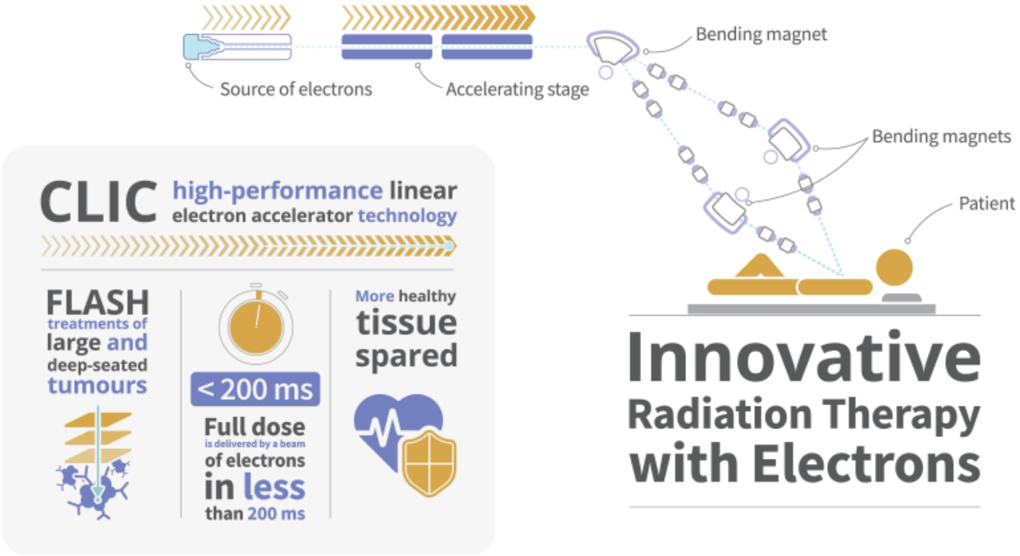
CERN, CHUV and now THERYQ are actively collaborating on the realization of a clinical facility for the treatment of large, deep-seated tumors by a VHEE beam in FLASH conditions

The target is a facility that:

- Uses 100 MeV-range electrons and optimized dose delivery.
- Is compact enough to fit on a typical hospital campus.

The collaboration demonstrated that the facility is feasible and are now finalizing the details of its technical implementation aiming at first clinical tests in 1-2 years

If successful, the facility may open the way for many future VHEE/FLASH facilities

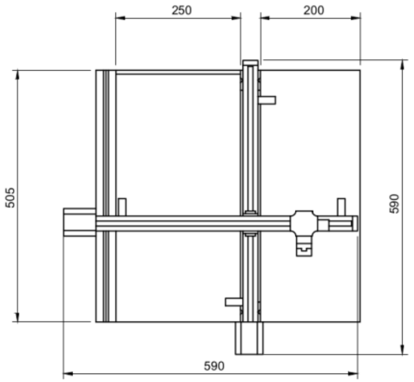


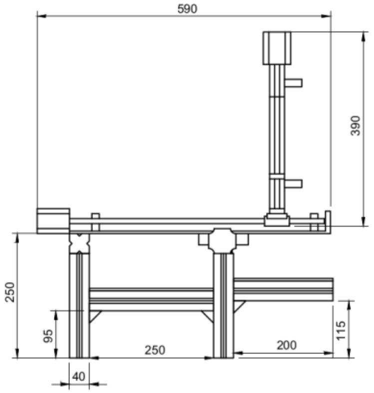
The CLEAR-Robot

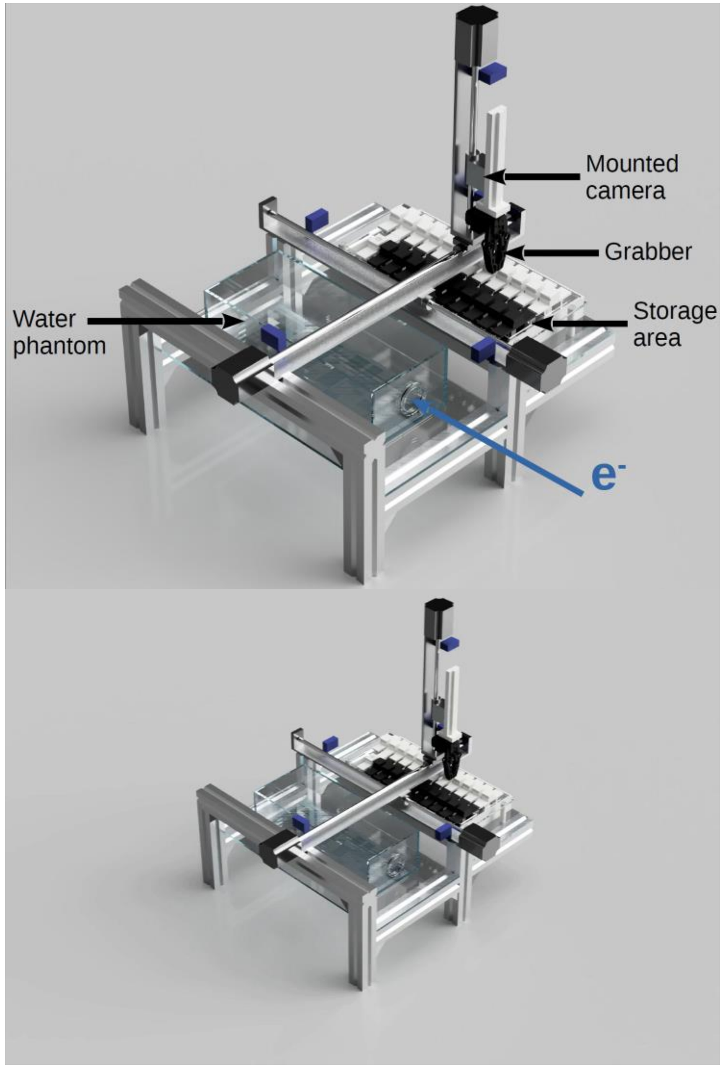
In order to facilitate the precise control of samples for multiple irradiations, the CLEAR-Robot (C-Robot) was designed and built by members of the CLEAR Operation Team.

- 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: https://pkorysko.web.cern.ch/C-Robot.html
- Used for 100% of Medical Applications in CLEAR in 2023.

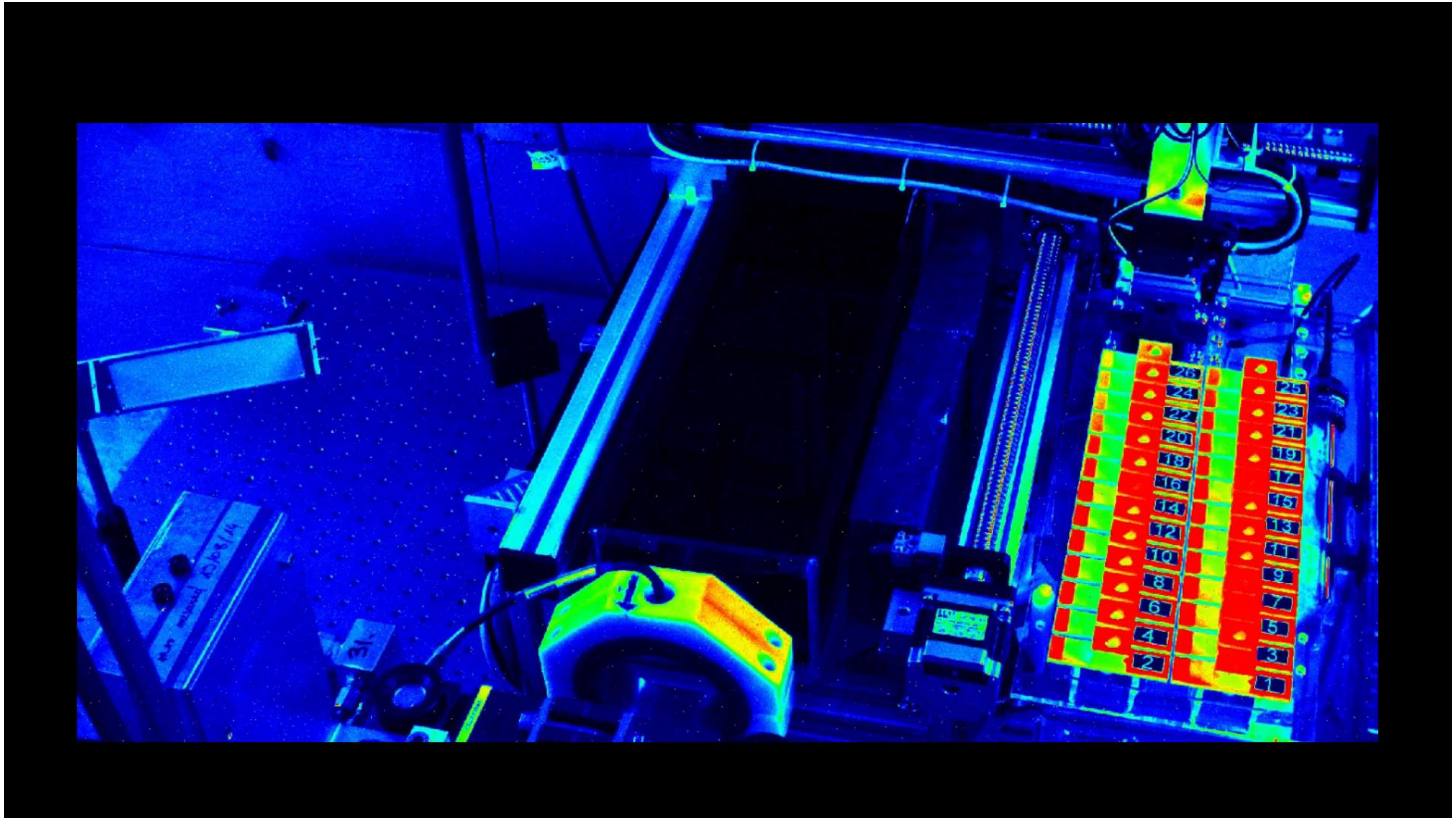
P. Korysko







The C-Robot in action with beam

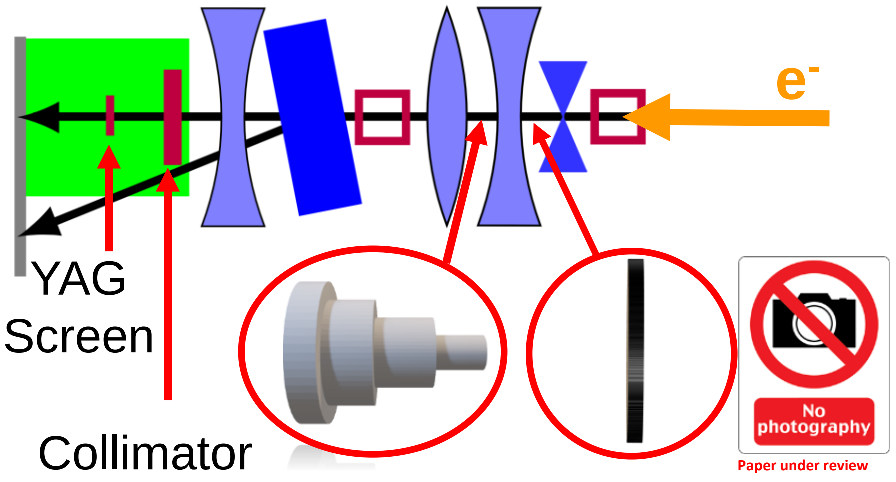


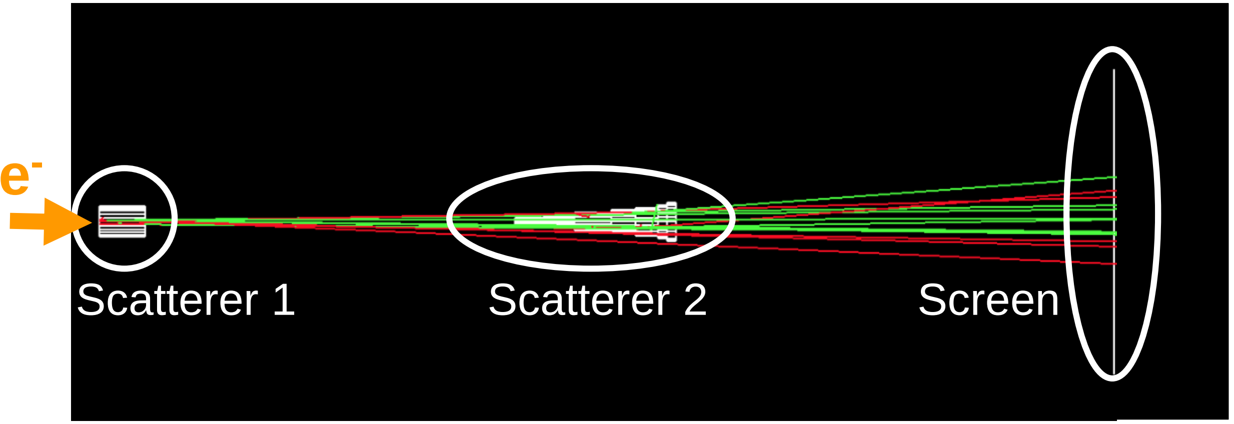
P. Korysko

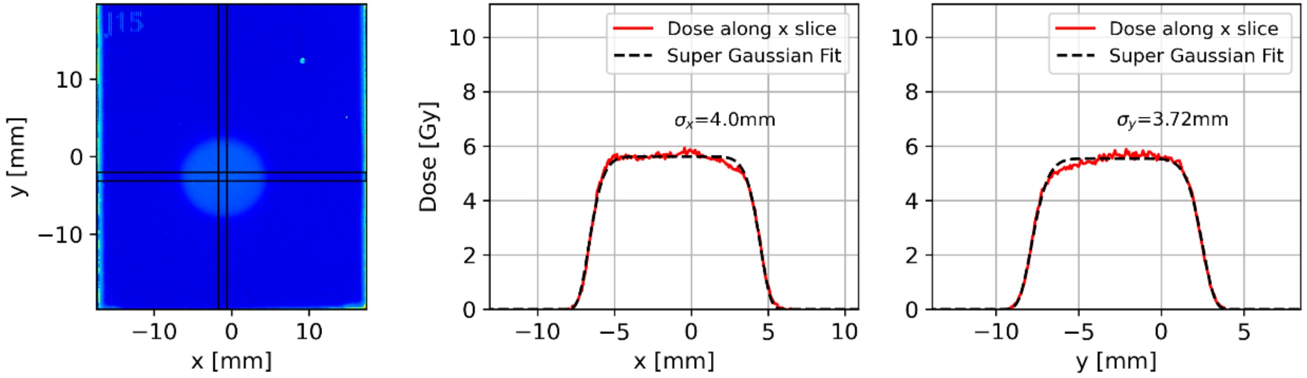
The double scatterer system – uniform beam

Goal:
Obtain a flat beam that has a constant transverse distribution at the sample (or at patient's tumor).

Method:
Use two scatterers – the second one with a special shape – to redistribute transversally the beam from the accelerator, which initially has a gaussian profile







X and Y beam profile

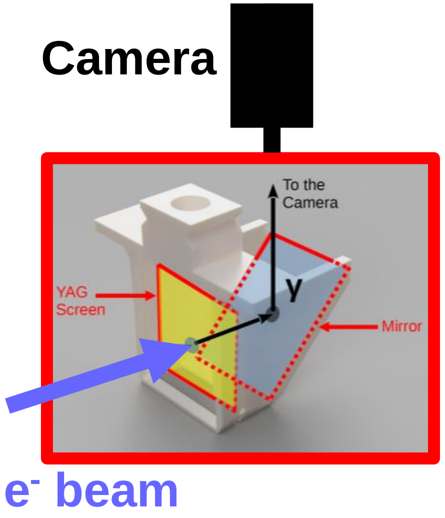
Now used by CLEAR Operation.

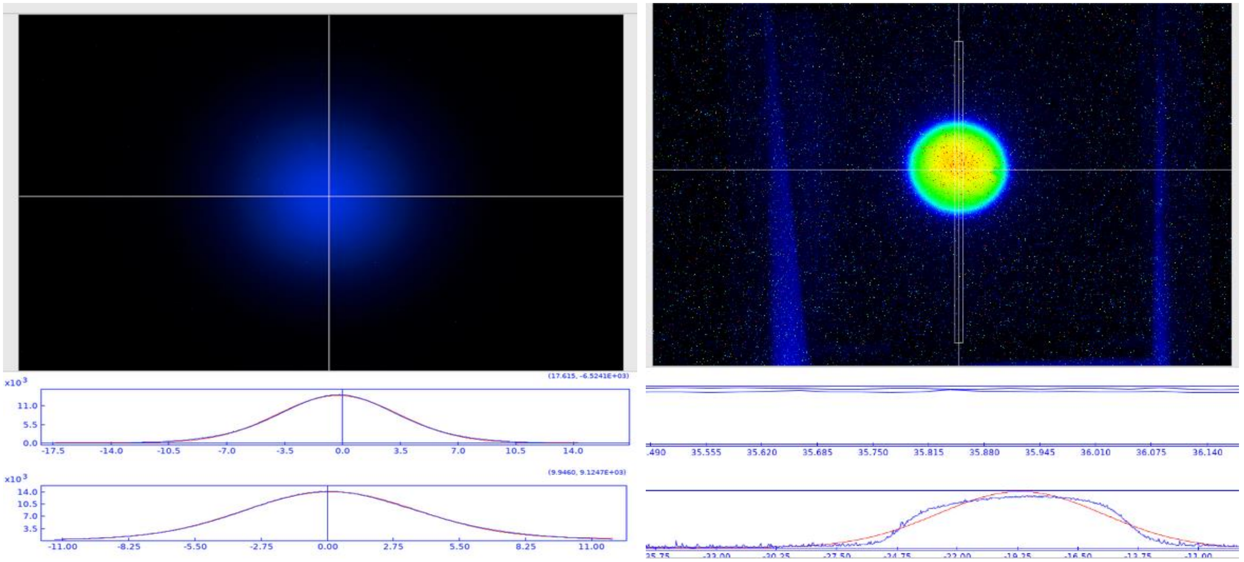
C. Robertson

Real time dosimetry

Issue: standard real-time dosimetry by ionization chambers do not work well with UHDR (nonlinear response)

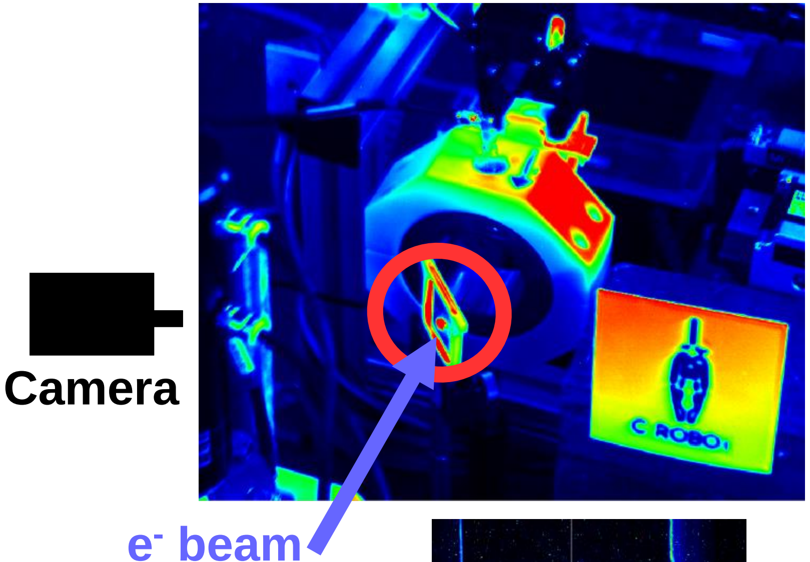
V. Rieker, A. Malyzhenkov, J. Bateman

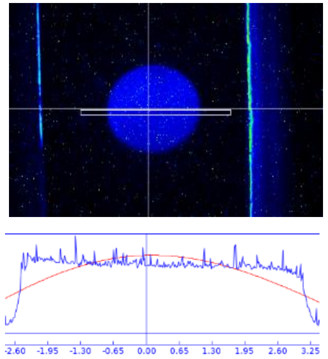




Gaussian Beam

Uniform Beam

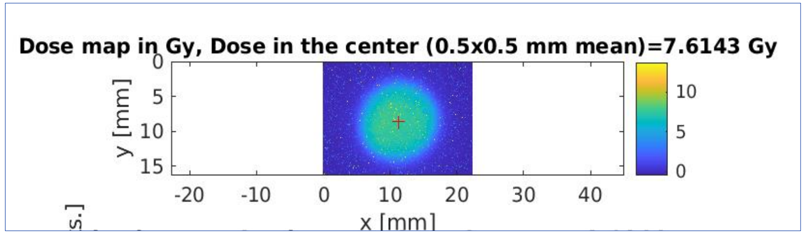




- In CLEAR we developed a fast dosimetry method by measuring the beam charge, and the beam size with a scintillating screen. The samples are then irradiated at the same exact location.

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

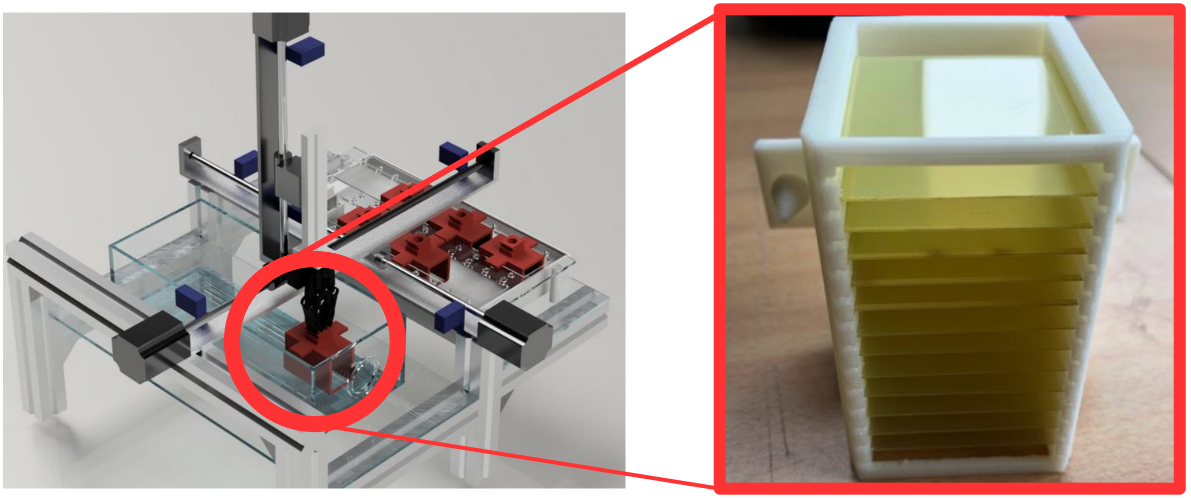
- Alternative methods, e.g. using optical fiber arrays, are also being developed in CLEAR.

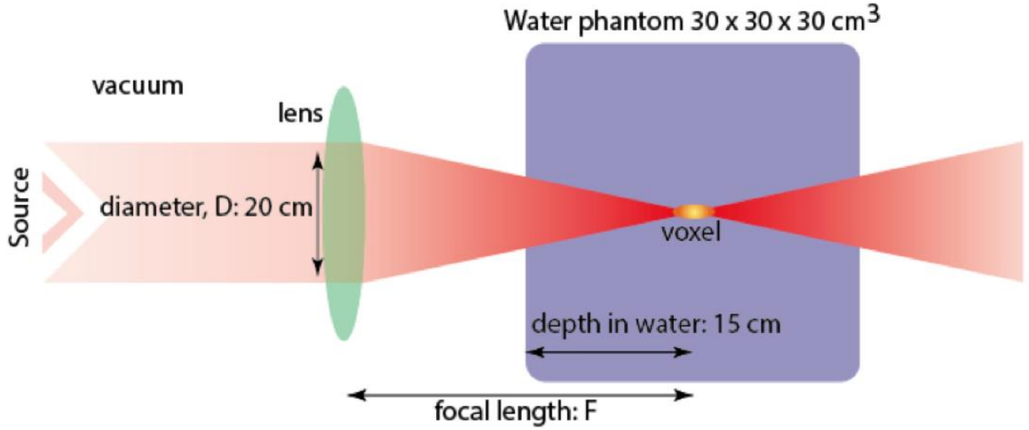


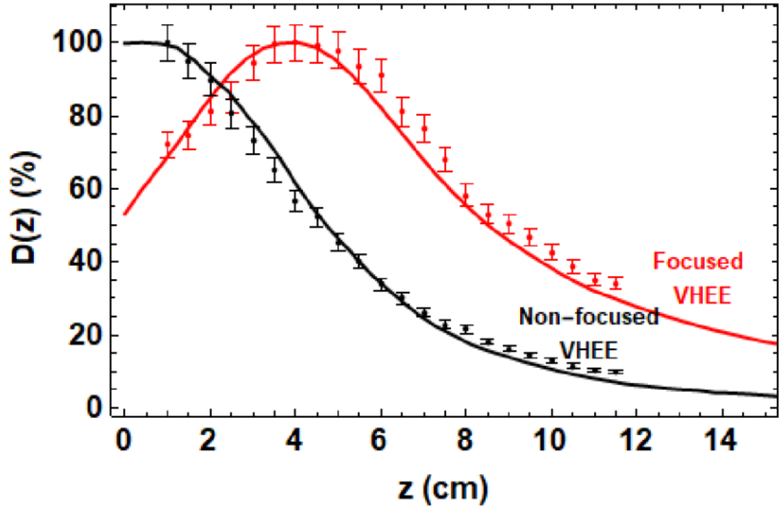
VHEE strong focusing

Goal:
Focus the beam on the tumor in order to minimize the dose and damage on the nearby healthy tissues.

Experiment:
Measure the beam sizes with a YAG screen in the water phantom (good model of the human body) and perform irradiations on radiochromic films placed at different longitudinal positions.







Published in Nature Scientific Reports

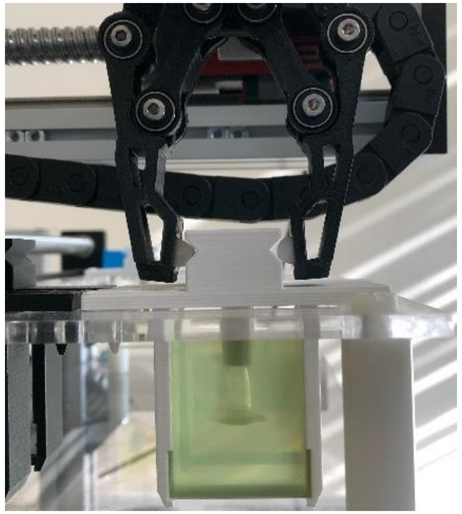
L. Whitmore

VHEE/FLASH chemistry studies

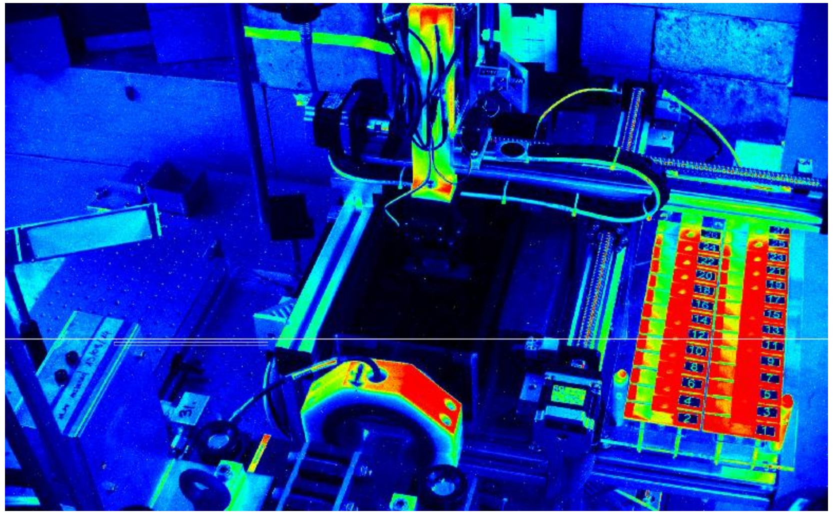
Experiment:

Measure and compare the production of Reactive Oxygen Species (ROS) in water at Conventional Dose Rate (CDR) and Ultra High Dose Rate (UHDR).

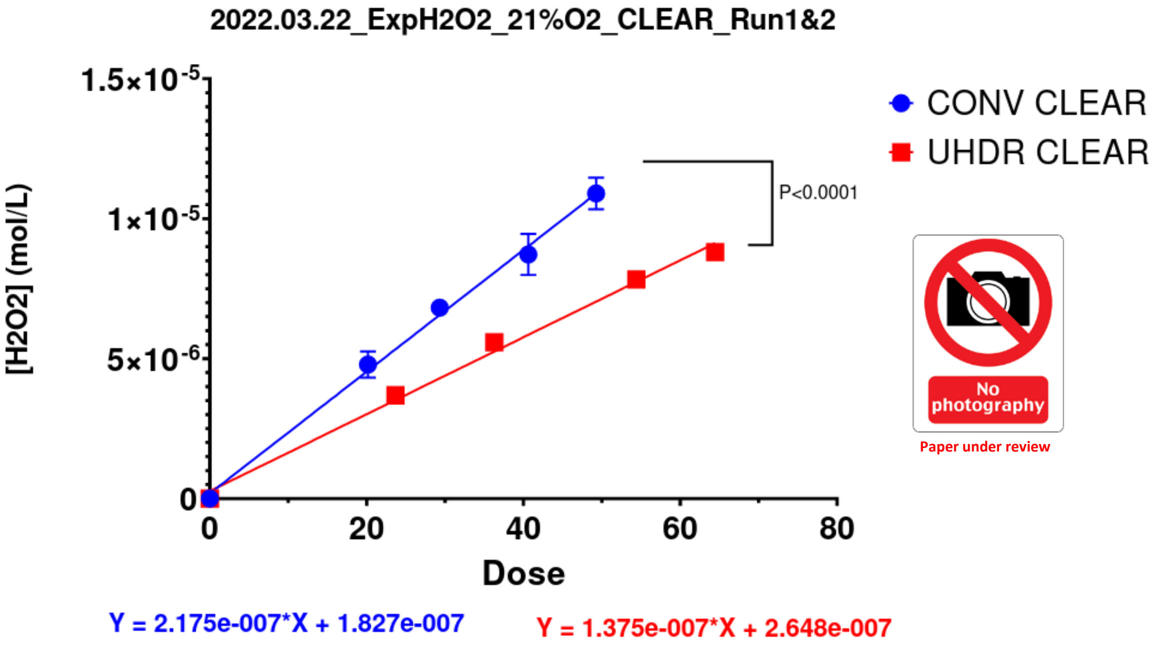
UHDR=1.2 10^9 Gy/s **CONV=0.15-0.41 Gy/s**



Holder with films and Eppendorf tube



C-Robot view when performing irradiations for chemistry studies



M-C. Vozenin & H. Kacem

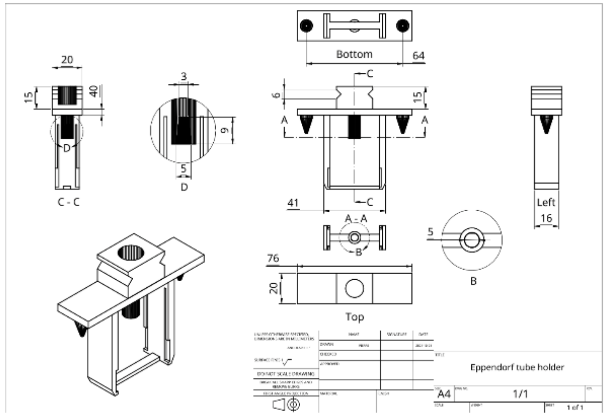
VHEE/FLASH Biodosimeter irradiation

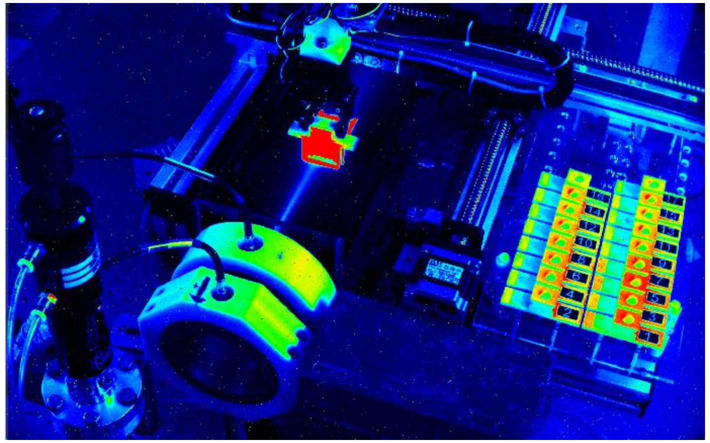
Goal :

Measure the response effect of the dose and the dose rate on biodosimeters with VHEE.

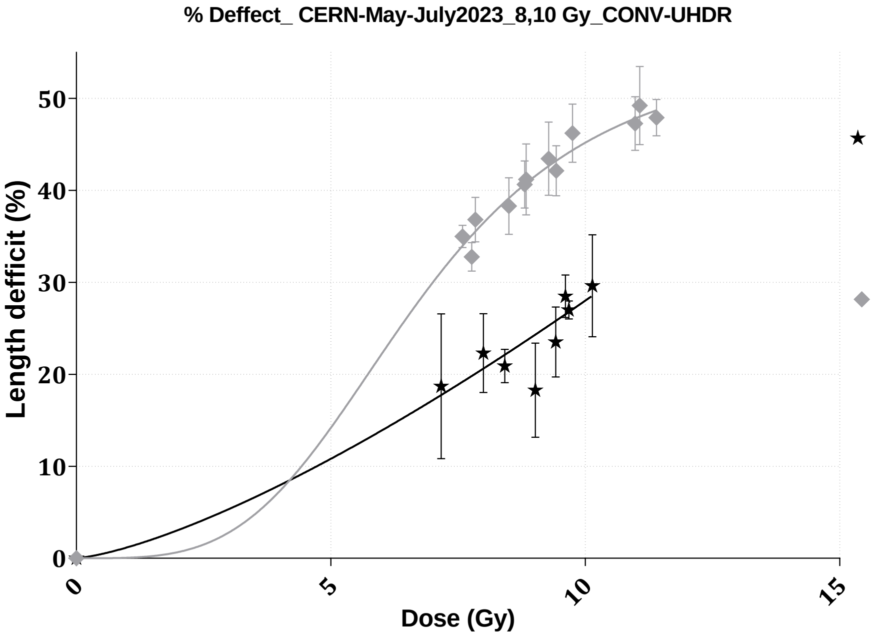
Experiment :

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





Preliminary results



Paper under review

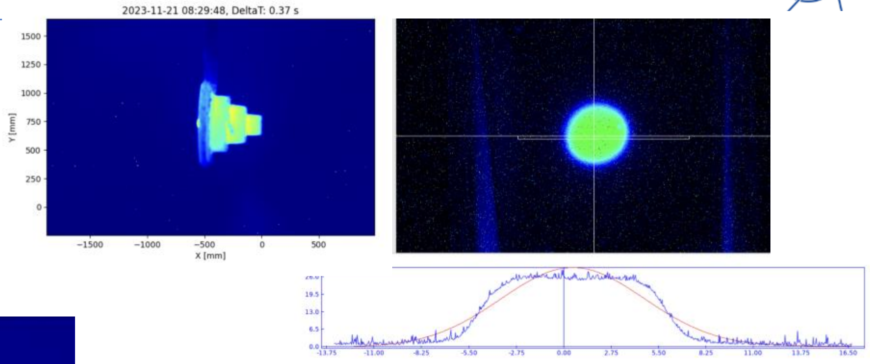
M-C Vozenin & J. Ollivier

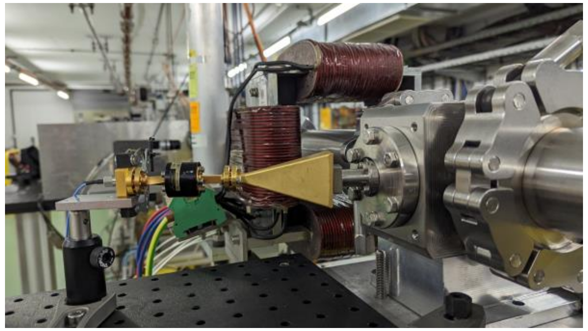
Operation 2023

- 27 Experiments
- About 21 User Groups internal/external
- More than 18 external collaborating institutes
- Beam from February 27th to December 15th (with 3 weeks summer stop)
- 38 weeks of operation in total

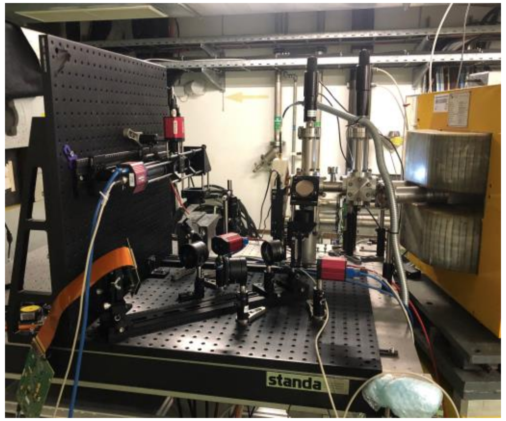
A few Highlights

Double-scattering system for uniform beam delivery for VHEE radiotherapy (CERN/Oxford U.)

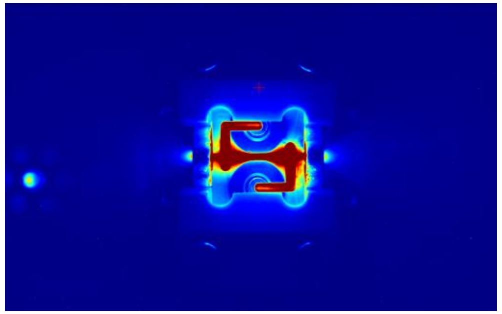




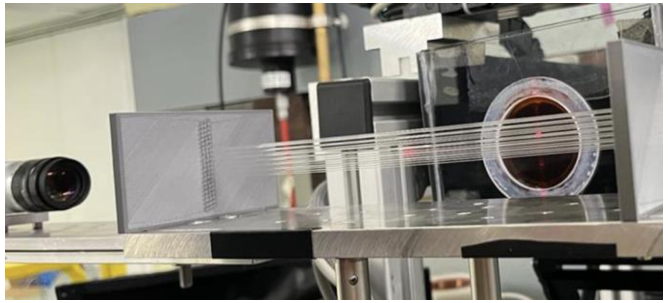
AWAKE Cherenkov Diffraction Radiation BPM



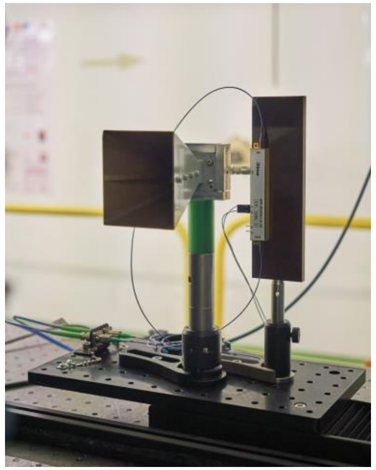
Novel OTR-based emittance meas. system for AWAKE (Liverpool U.)



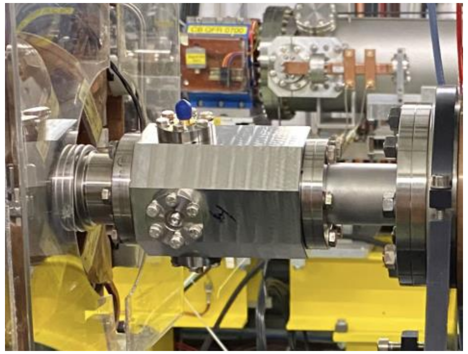
Plasma lens defocusing tests (Oslo U./CERN/Oxford U./DESY)



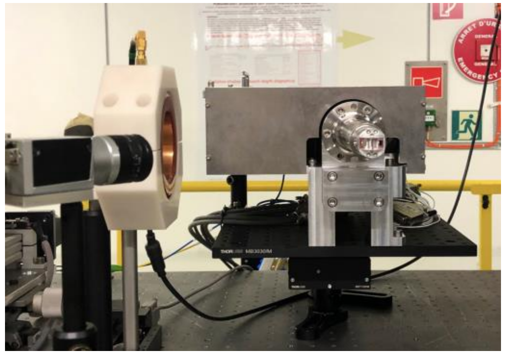
Fibre-optic beam profile and dose monitor for VHEE radiotherapy at ultra-high dose dates(CERN/Oxford U.)



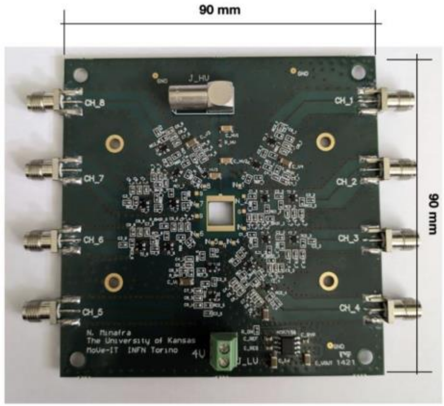
Coherent Cherenkov diffraction radiation dielectric buttons (FCC-ee bunch length monitors)



Broadband Pick-up for the PSI Positron Production Project (FCC-ee collaboration)

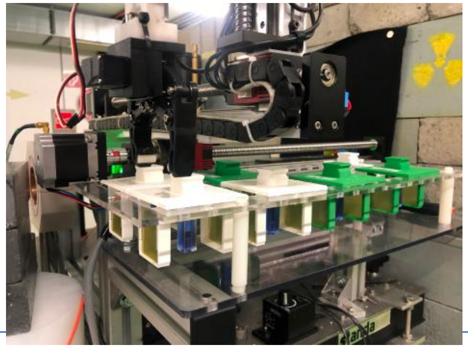


Bunch Profile Monitor for FCC-ee (Karlsruhe)



Beam testing of PCB + detectors using different technologies (Kansas U.)

Real-time dosimetry for VHEE radiotherapy using cuvettes (Strathclyde U.)



MDs, accelerator physics, beam dynamics

Apart from user experiments, some beam time is dedicated to Machine Development(MD) sessions, aimed at improving beam quality and expanding the beam parameter space.

In some cases, MD activities in CLEAR constitutes also a relevant contribution to the field of accelerator physics and beam dynamics.

Enhancing particle bunch-length measurements based on Radio Frequency Deflector by the use of focusing elements

Pasquale Arpaia, Roberto Corsini, Antonio Gilardi, Andrea Mostacci, Luca Sabato & Kyrre N. Sjobak

Scientific Reports **10**, Article number: 11457 (2020) | Cite this article

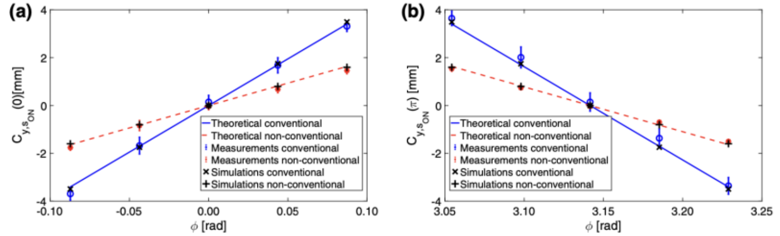
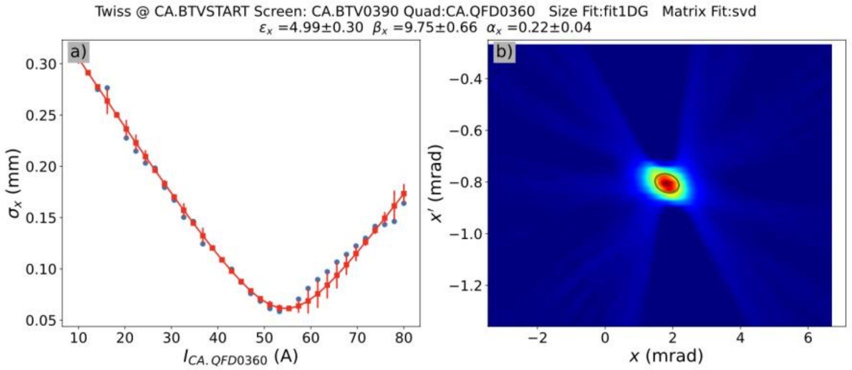


Figure 9. Vertical ($C_{y,ON}$) versus RFD phase in conventional and non-conventional layout around 0rad (**a**) and π rad (**b**): measurements (circle and star for conventional and non-conventional layout, respectively), theoretical values (solid and dashed lines for conventional and non-conventional layout), and simulation points (cross and plus sign for conventional and non-conventional, layout respectively).

A. Gilardi

Beam Tomography



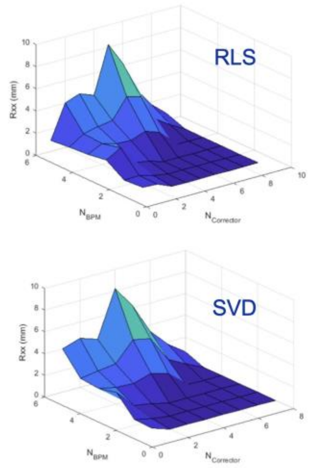
A. Aksoy

Beam Based Alignment

$$X = X_0 + R\Theta, \quad R_{i,j} = \frac{\Delta x_i}{\Delta \theta_j},$$

$$\Theta = (R^T R)^{-1} R^T \Delta X$$

DFS: $\begin{pmatrix} X \\ \omega(X - X') \\ 0 \end{pmatrix} = \begin{pmatrix} R \\ \omega(R - R') \\ \kappa I \end{pmatrix} \times \Theta,$



Operational BPMs allowed us to do high level beam physics.

We have developed an automated response matrix generation tool.

- Random or excitation in sequence of correctors for given machine setting
- R: for nominal energy, R' : for reduced energy

Based on chose one can create response matrix based on different algorithms (RLS, SVD) apply one-to one steering or DFS

Full process takes about 30 min

A. Aksoy

You will be joining some of these activities, including bunch length measurements and quadrupole scans during this week.

Thanks for your attention!

See you later in CLEAR