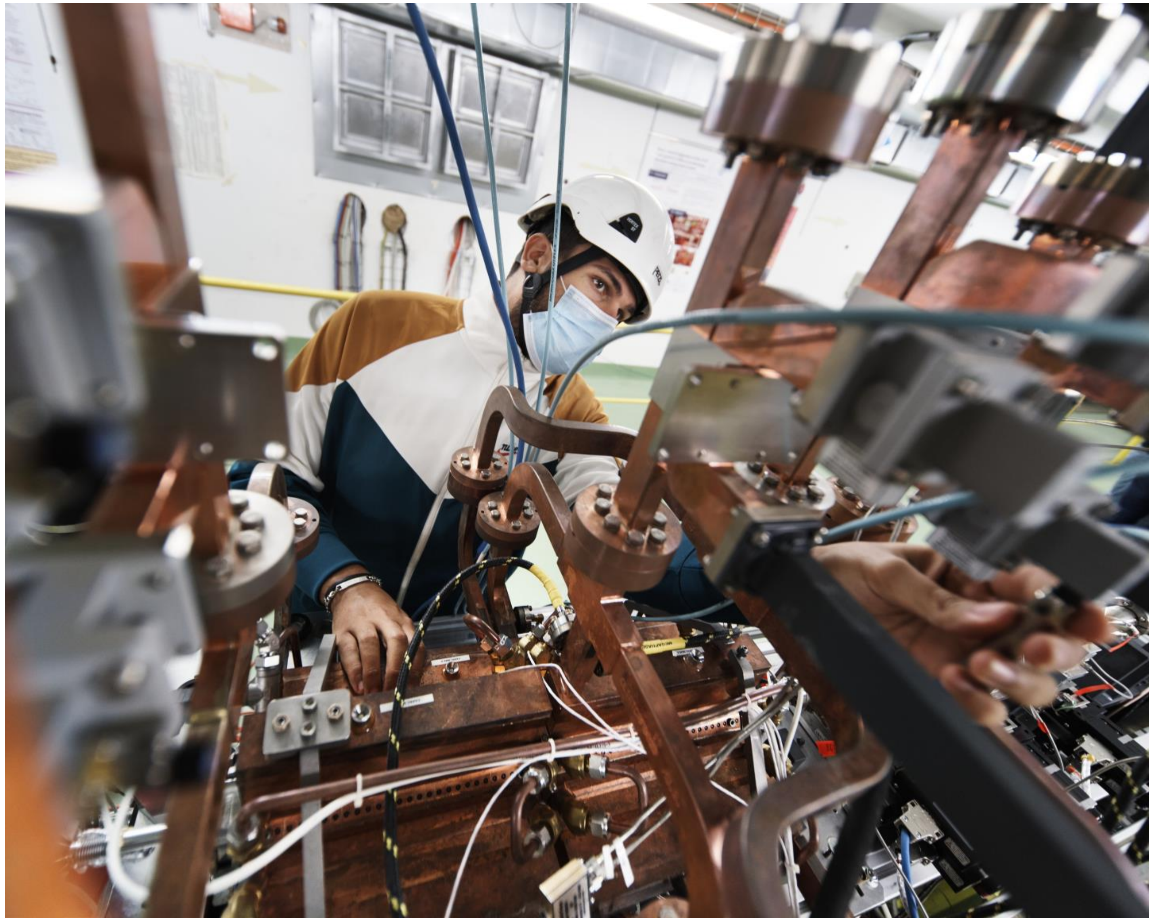
Introduction to the CLEAR Facility and present status

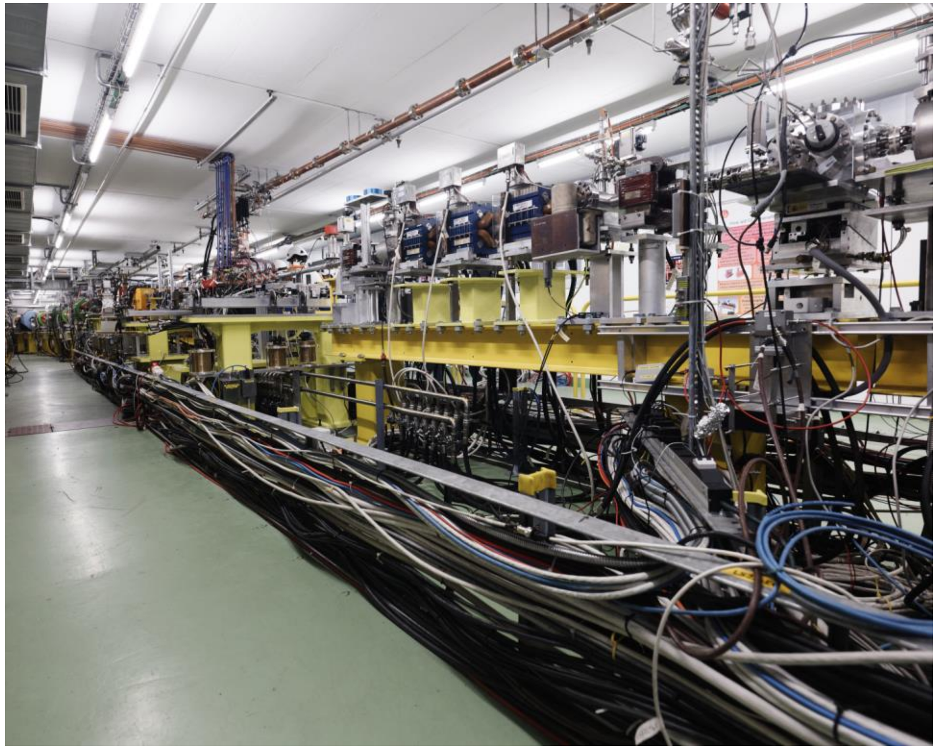
R. Corsini

Outline

- Introduction to CLEAR:
  - Short description
  - Evolution
  - Operational mode
  - Main activities



The CERN Linear Electron Accelerator for Research (CLEAR)

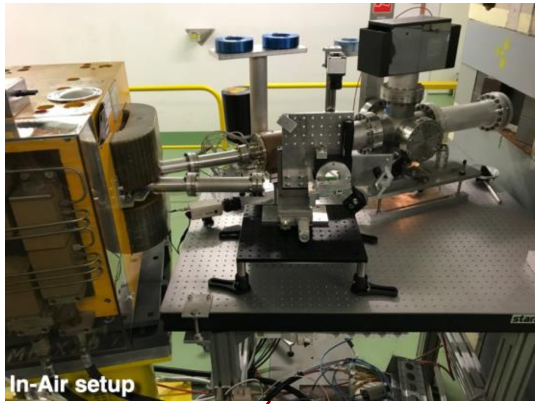


CLEAR is a versatile 200 MeV electron linac + a 20 m experimental beamline, operated at CERN as a multi-purpose user facility.

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.

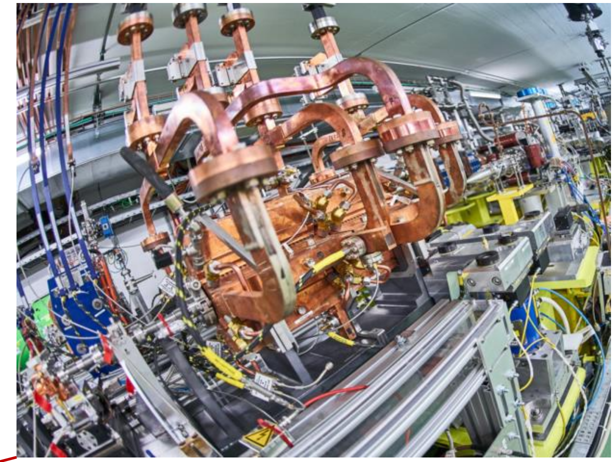
CLEAR Layout & main installations



In-air test stand

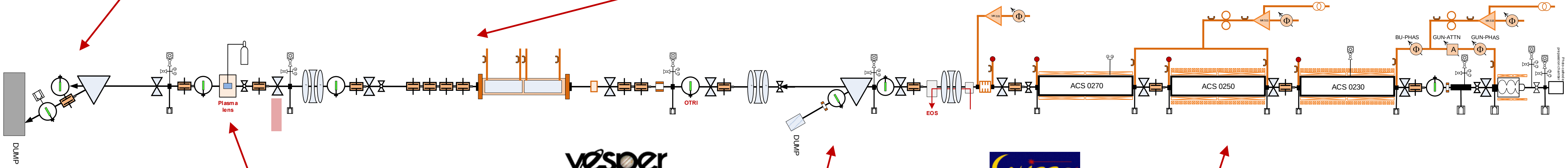
Testing ground for beam diagnostics R&D and THz radiation studies

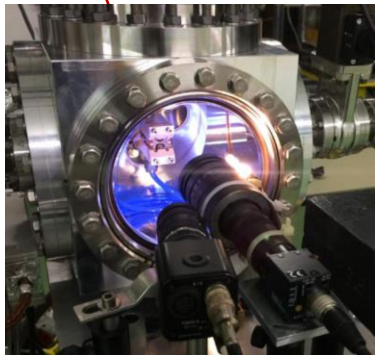
Irradiation for medical and other applications



CLIC Test-Stand

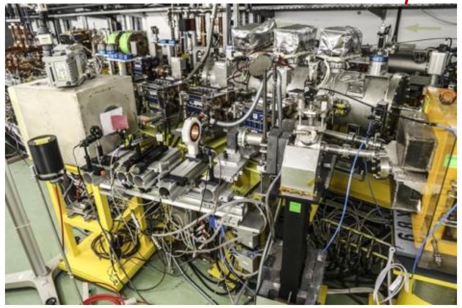
High-gradient and linear colliders R&D





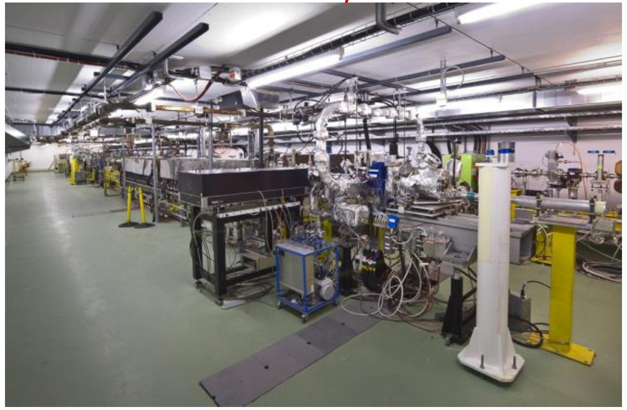
The Plasma Lens Experiment

Novel concepts of plasma-based focusing and acceleration



VESPER

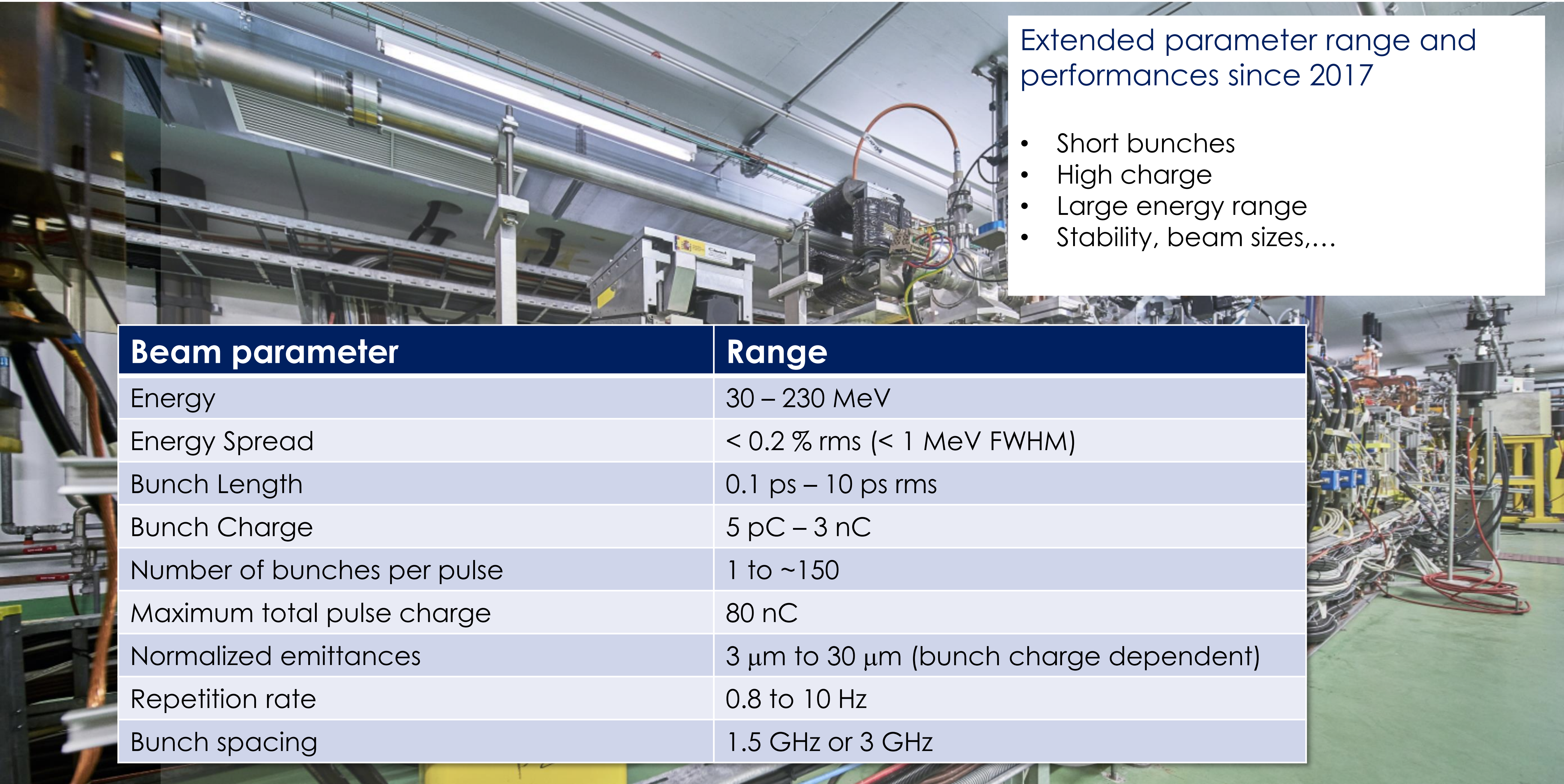
Beam irradiation facility for studies on radiation damage of electronics and medical applications



CALIFES electron linac

Flexible accelerator providing 200 MeV electron beams to all CLEAR users

CLEAR Beam Parameters



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

CLEAR Timeline

- Approved in December 2016, as a 2 + 2 years program
- Started operation in August 2017
- Reviewed and extended until 2020 in February 2019
- Operation extended in 2021 and possibly beyond, with independent budget included in the new CERN Medium Term Plan 2021-2025 (approved by the CERN Council in September 2020)
- CERN internal review, 16 March 2021 → confirmed, approved to end 2025

Main activities

- Beam Diagnostics R&D

  SY/BI is our main interface, collaboration with external institutes, or other CERN projects mainly through them

- Medical Activities

  Main collaborator is CHUV-Lausanne, but independent collaborations exist with several other institutes/firms

- Irradiation

  Similar to beam diag R&D, our main interface is the R2E team at CERN – collaboration with others (e.g., ESA) handled jointly

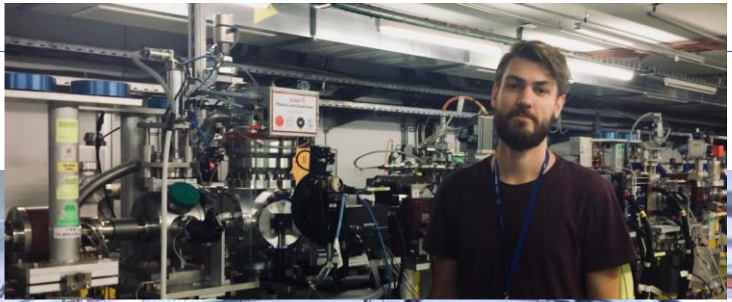
- Advanced acceleration

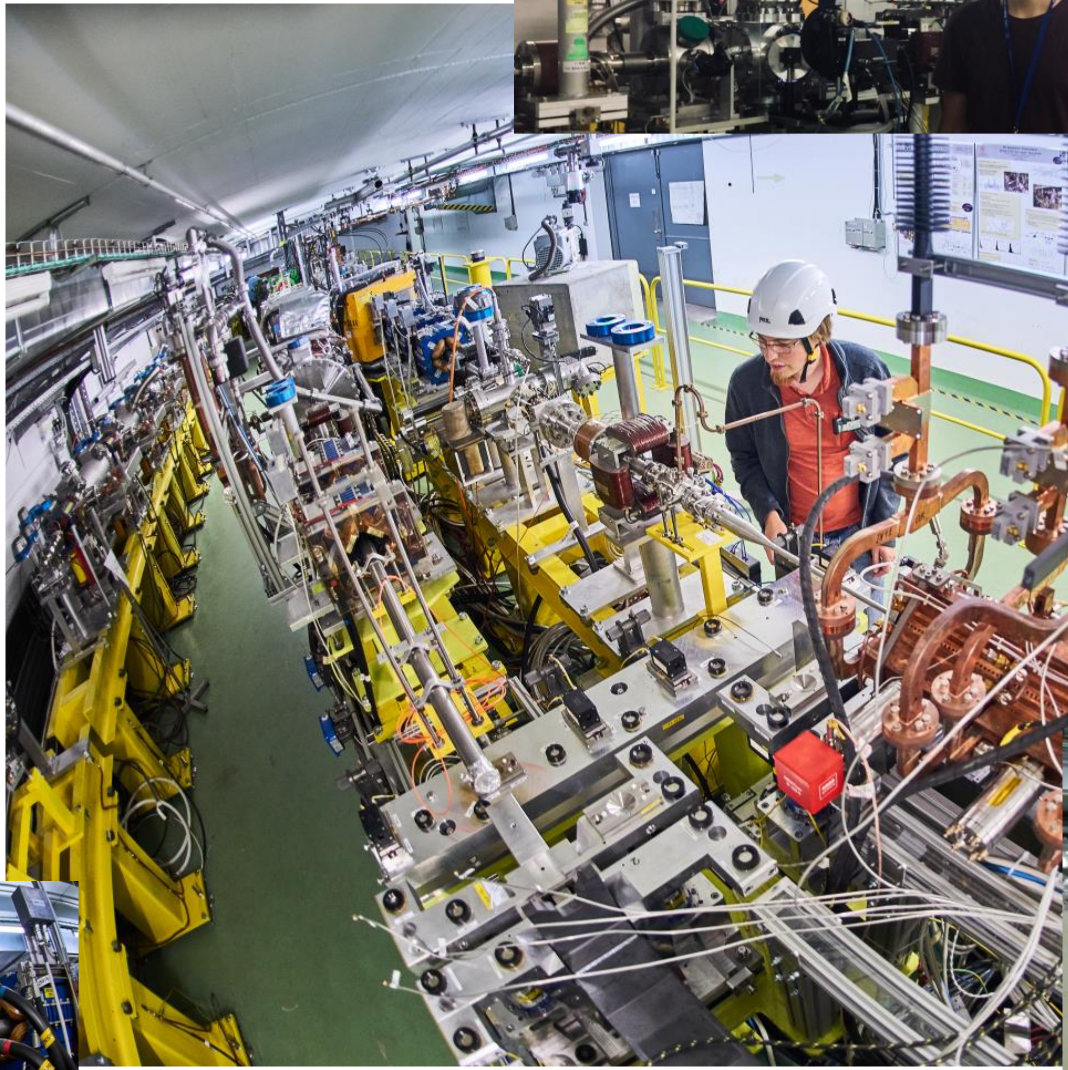
  Two main "clients" so far: CLIC and AWAKE, plus the Plasma Lens Collaboration lead by Oslo University

- Others

  We routinely receive (and follow) beam time requests in many different fields, different from the above. One example is the testing of micro-Beam Profile Monitors we do for the IRRAD facility at CERN - other examples later

CLEAR operation 2017-2020





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
- 40 weeks in 2022

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 in 2020)

- Current operating team:
  1 Staff, 1 associate, 1 fellow, 2 PhD students, 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)

Access to beam time

- Any user willing to access the facility has to fill-up a beam time request form (https://clear.cern/content/beam-time-request), specifying:
  - Experiment description, scientific aim and justification
  - Needed beam parameters
  - Experimental apparatus and logistics, safety aspects

- In general, some iterations between the operation team and the requester are needed (before or after receiving the form) in order to clarify requirements and understand goals.

- The CLEAR Technical Board is responsible to give the final authorization and allocate the beam time in the schedule, after checking technical feasibility and scientific interest and safety and RP issues, following guidelines by the CLEAR Scientific Board

- The CLEAR Scientific Board members are also involved in the formal approval procedure for each beam time request, which is carried out using the CERN EDMS infrastructure

- User teams often ask for beam time for an activity a few times during a year, and often over 2 or more years. Beam time requests beyond 1 year require to fill out a new form

Irradiation on electronics

CLEAR has been central to R2E activities over the last 5 years

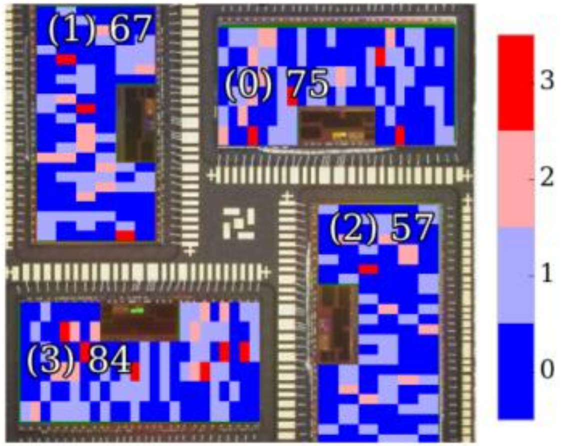
- Initial interest for Jovian environment space missions (JUICE from ESA)

Electron-induced effects in electronics are **not as well explored** as those from ions, protons or neutrons. CLEAR is central to the investigation of these effects.

- It enabled studying **key radiation effects** that it was not possible to study elsewhere

- Explored electron-induced **single-event effects** over a wider range of energy than what can be achieved in medical LINACs.
- Enabled **first ever observation** and demonstration that HEE can trigger SEL in SRAM.
- It enabled studying **displacement damage** effects in a short time and with low level of activation
- Allowed studies on HEE SEU, SEL, stuck bits…

S. Coronetti



ESA Monitor
(reference chip, 250 nm)

Publications

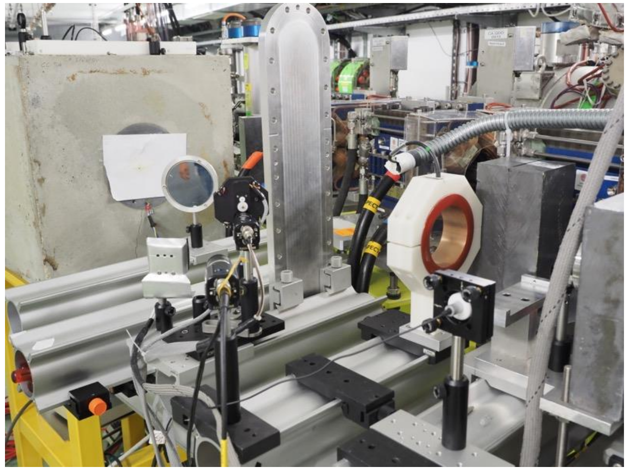
- M. Tali et al., "High-Energy Electron-Induced SEUs and Jovian Environment Impact," in IEEE Transactions on Nuclear Science, vol. 64, no. 8, pp. 2016-2022, Aug. 2017.
- M. Tali et al., "Mechanisms of Electron-Induced Single-Event Upsets in Medical and Experimental Linacs," in IEEE Transactions on Nuclear Science, vol. 65, no. 8, pp. 1715-1723, Aug. 2018.
- M. Tali et al., "Mechanisms of Electron-Induced Single-Event Latchup," in IEEE Transactions on Nuclear Science, vol. 66, no. 1, pp. 437-443, Jan. 2019.
- M. Tali, " Single-Event Radiation Effects in Hardened and State-of-the-art Components for Space
- and High-Energy Accelerator Applications", PhD Thesis, University of Jyväskylä, Finland, 2019.
- A. Coronetti et al., "SEU Characterization of Commercial and Custom-designed SRAMs manufactured in 90 nm technology and below", in IEEE Radiation Effects Data Workshop, Santa Fe, NM, USA, 2020.
- D. Söderström et al., "Electron-induced Single Event Upsets and Stuck Bits in SDRAMs in the Jovian Environment", accepted for publication in IEEE Transactions on Nuclear Science, 2021.
- D. Poppinga et al., "VHEE beam dosimetry at CERN Linear Electron Accelerator for Research under ultra-high dose rate conditions", Biomedical Physics Express, vol. 7, no. 1, 2021.

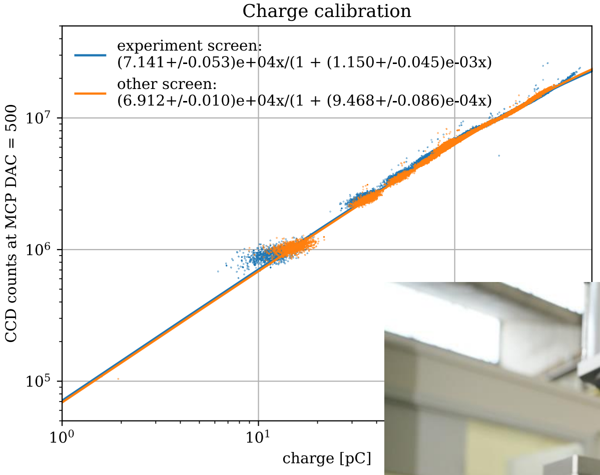
And more are coming...

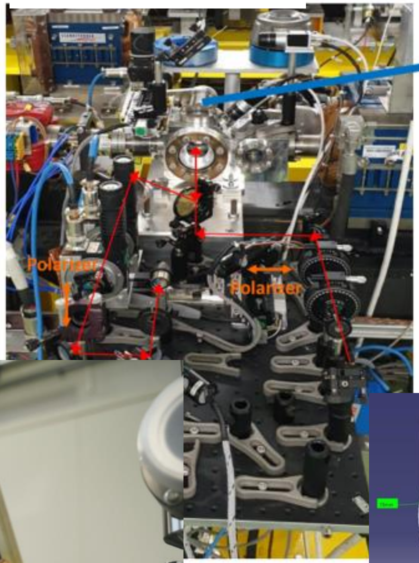
AWAKE

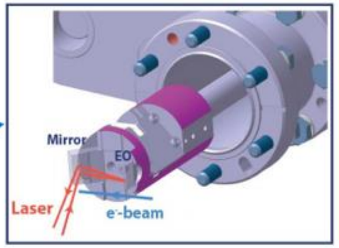
E. Gschwendtner

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



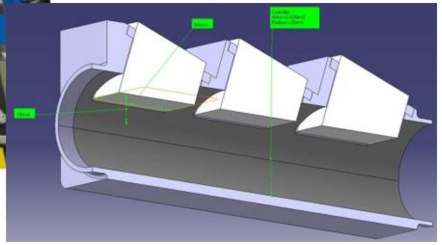


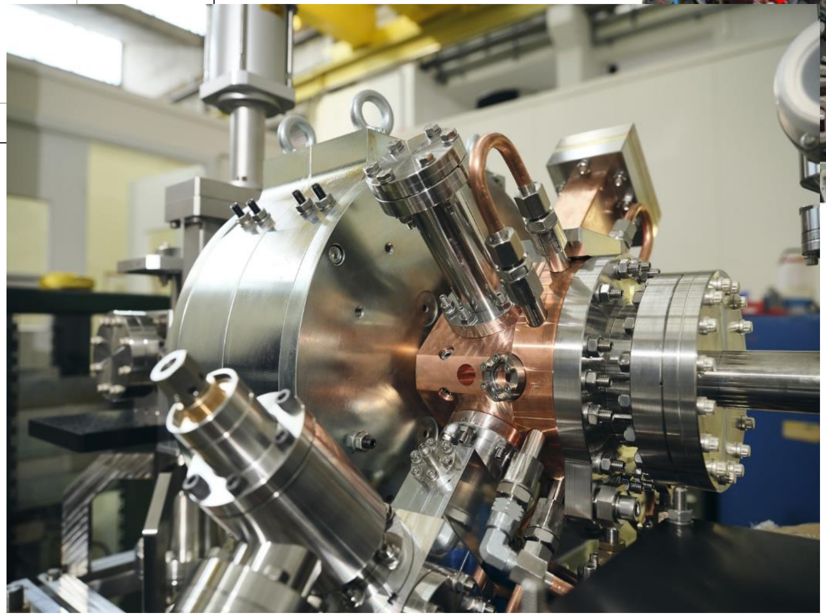




Bunch length monitors:

EOS and ChhDR



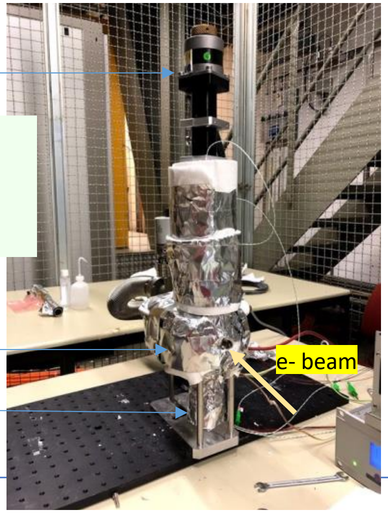


Common development of novel electron source

CLIC-AWAKE-CLEAR

Cherenkov BPMs

Beam Screen Survival Tests in Rubidium



CLIC

S. Stapnes

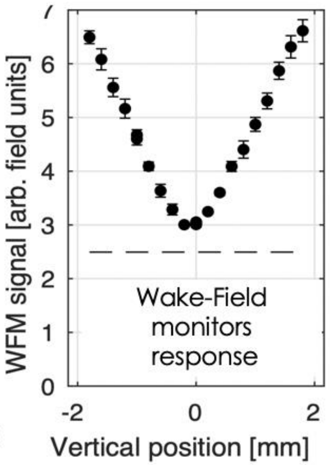
Key CLIC related activities

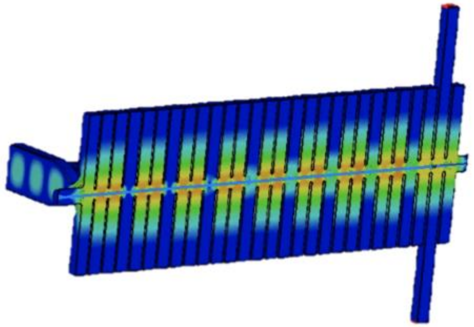
Experiments:
- Wake-Field monitors
- Wake-field kicks
- CLIC cavity BPMs

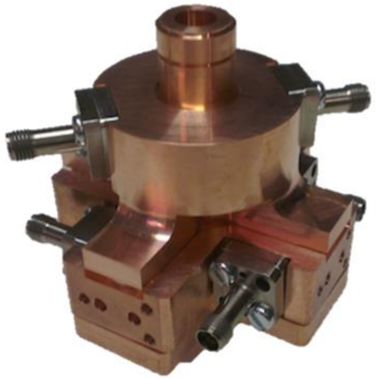
Main collaborators
- University of Oslo
- CEA - Saclay
- Università di Napoli Federico
- RHUL

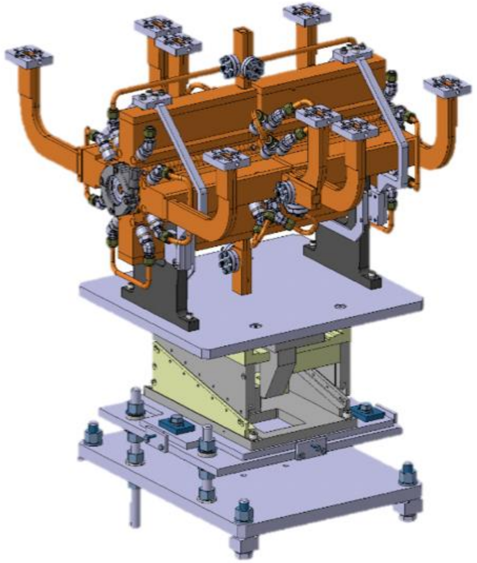
Future step, connecting the cavity to X-Box1

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

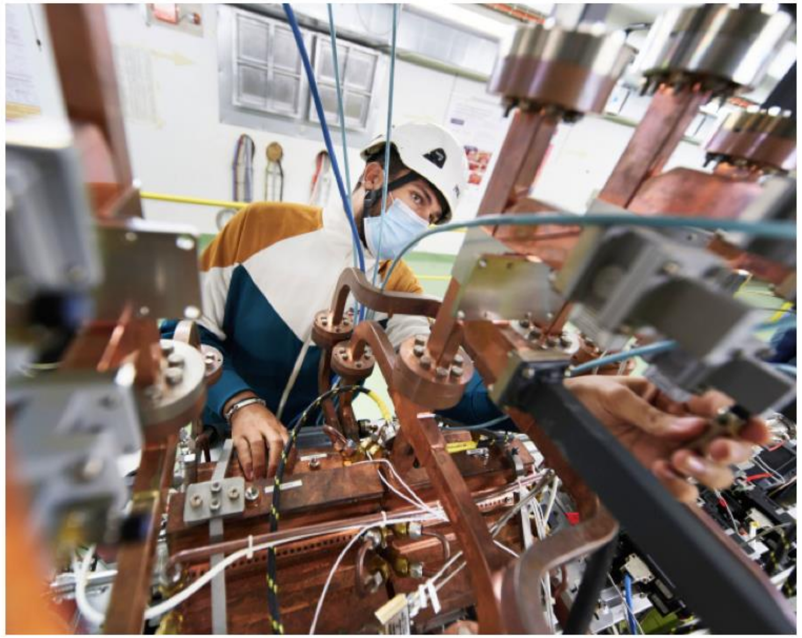








A. Gilardi, K. Sjobaek, M. Wendt, A. Lyapin

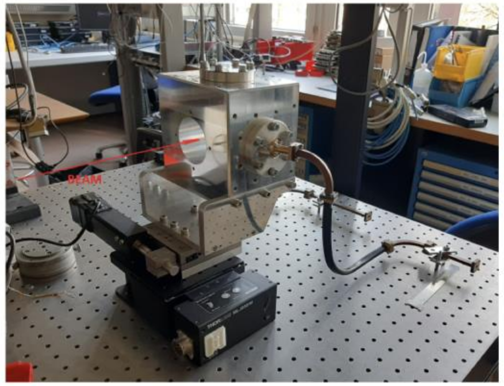


Cavity BPM and X-band structure on movers

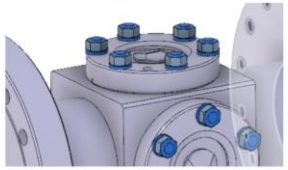
Other Beam Instrumentation activities

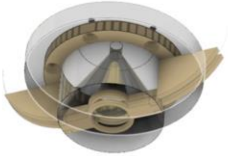
S. Mazzoni

- **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





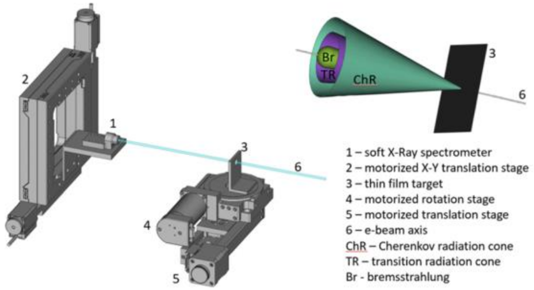
Recent Publications

- 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, ...)

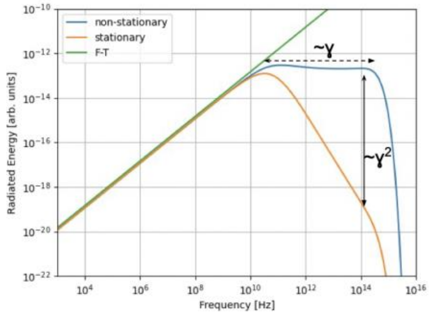
- **Optical BLM tests** (CERN)
  - Test of new optical BLM. Loss signal: Cherenkov Radiation produced in fibres.
  - 2020: measurement of ChR as a function of angle to benchmark simulations
  - 2021: improved read-out electronics and new sensors (SiPM, PMT, PD) test with low intensity bunches / trains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

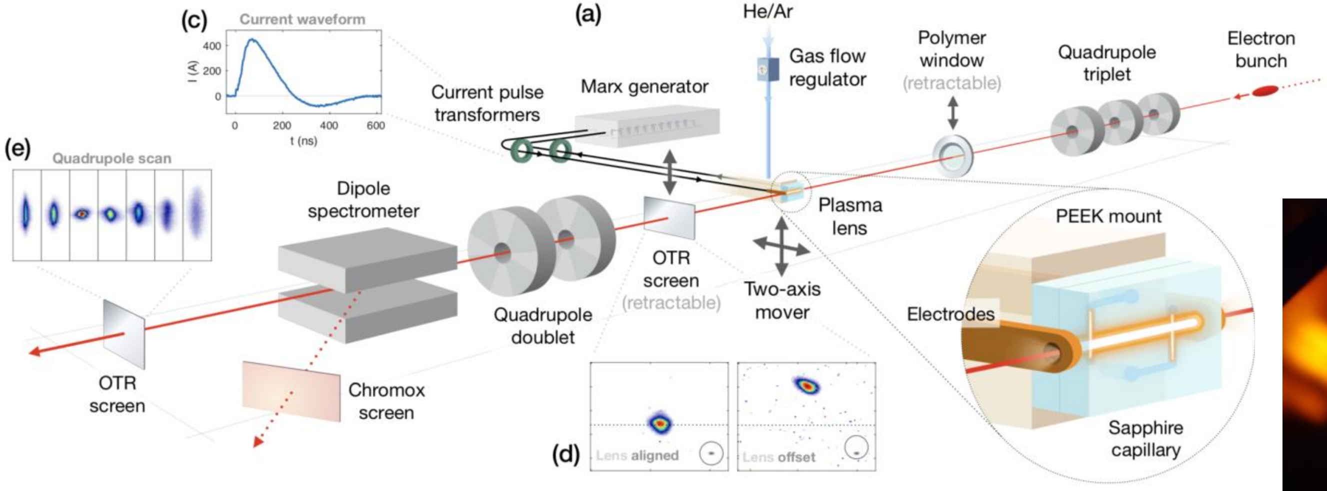


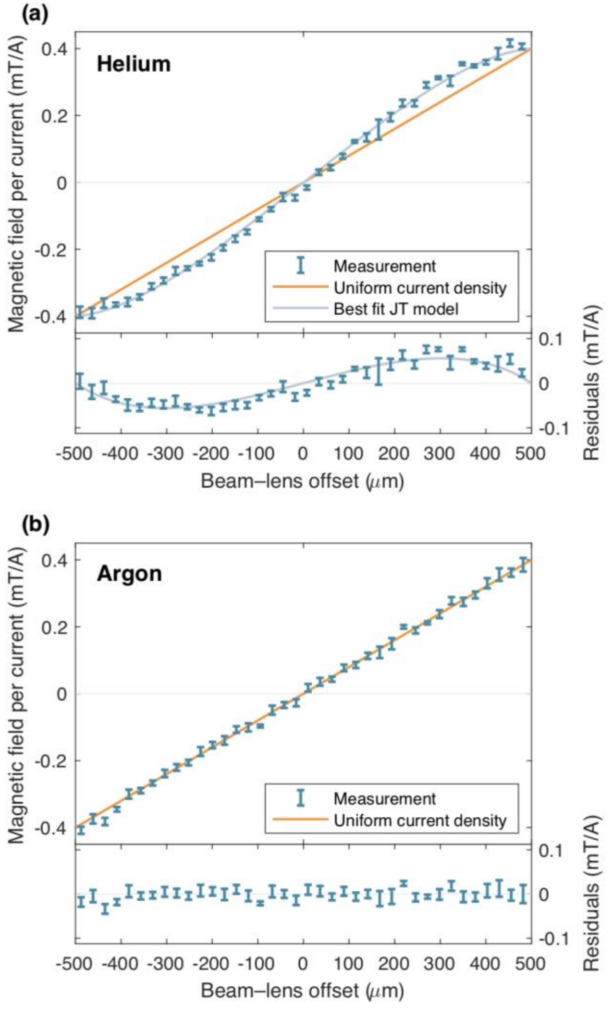
The Plasma lens experiment

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… in Helium.

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.

clear

VHEE at CERN – Background & Motivation

CERN

- The idea of investigating the use of very high-energy electron (VHEE) beams (50-250 MeV) for RT recently gained interest, since electrons at these energies can travel deep into the patient.
- Potential advantages:
  - Depth – dose profile for electrons better than the quasi-exponential decay given by X-rays
  - Charged particles like electrons may be focused and steered in ways that are 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 especially true given the recent advancements on high-gradient acceleration, e.g. X-band CLIC technology.
- Ultra-high dose rate (above 100 Gy/s) radiation delivery, termed FLASH radiotherapy, showed normal tissue sparing capabilities, without compromising tumor control. Electron linacs can relatively easily reach the high beam currents needed for FLASH treatment of large fields.

→ Exploit CERN expertise in accelerators, especially the one on high-gradient electron machines developed by the CLIC study. The CLEAR user facility offers as well a unique opportunity for experimental VHEE and FLASH studies with a high-current 200 MeV e- beam.

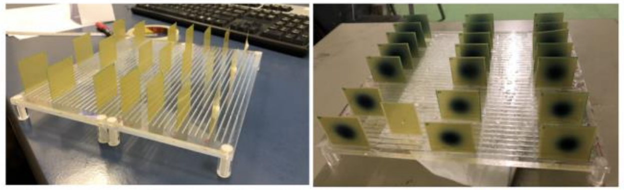
VHEE/FLASH activities in CLEAR

Calibration of operational medical dosimeters – nonlinear effects with high-dose short pulses

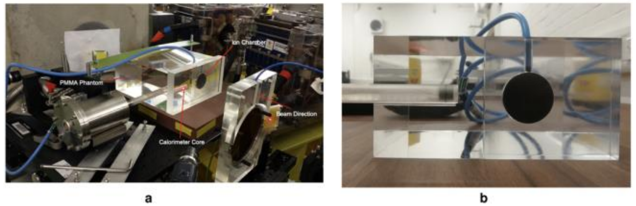
Verification of FLASH effect using biological dosimeters

Experimental verification of dose deposition profiles in water phantoms

Demonstration of "Bragg-like peak" deposition with focused beams



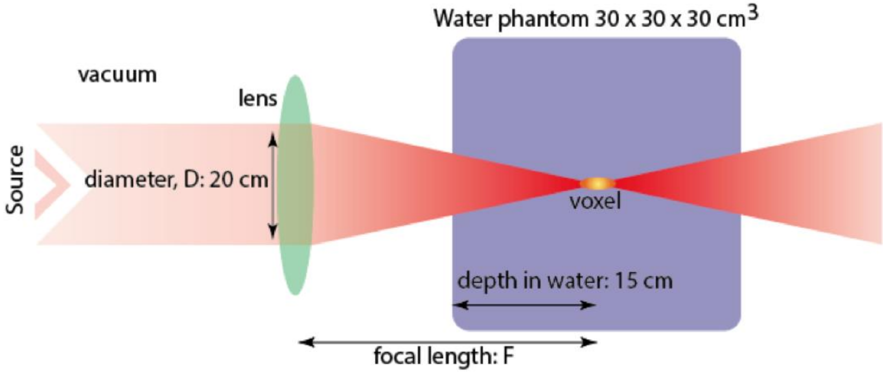
Films set-up for profile depth dose, CHUV Lausanne (M.C. Vozenin, C. Bailat, R. Moeckli et al.)



Calorimeter and ROOS chamber, Nat. Phys. Lab. UK (A. Subiel et al.)

High dose rate dosimetry

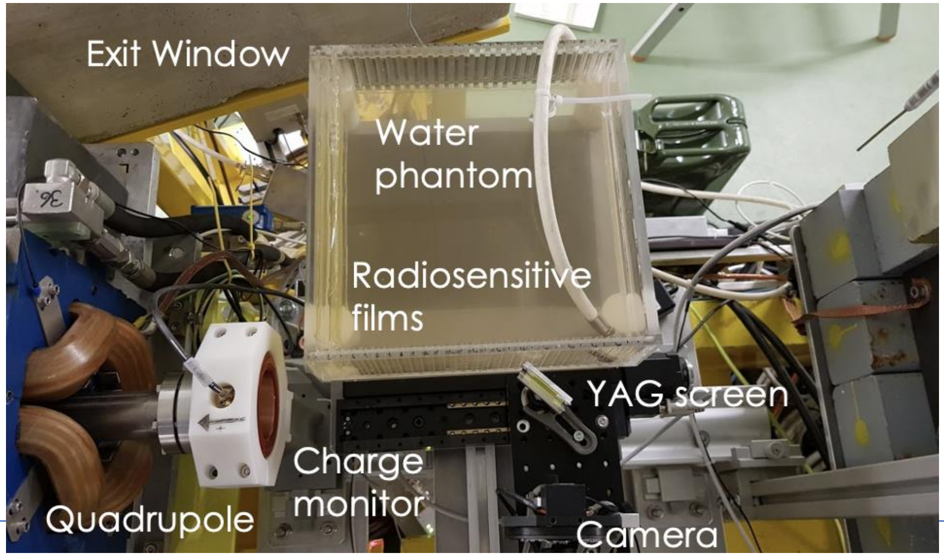
Advance Markus chambers and SRS Array, Oldenburg University and PTW (B. Poppe, D. Poppinga et al.)



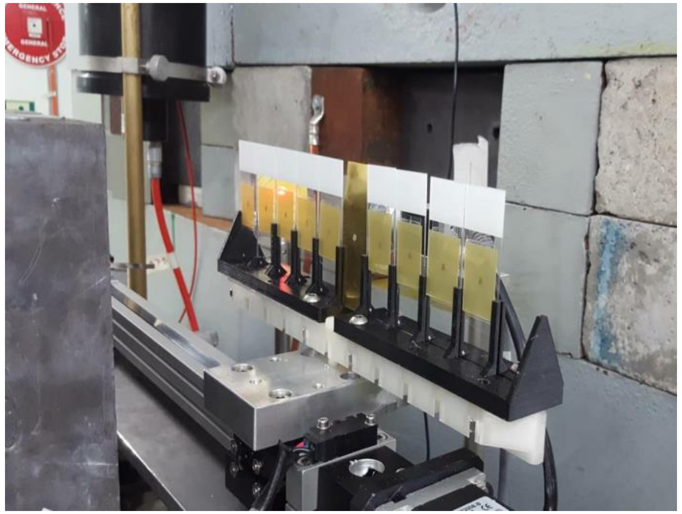
Aim:

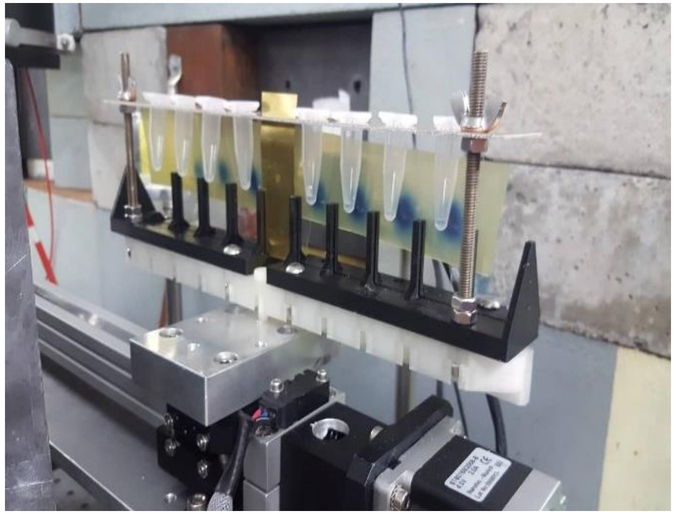
Focus the beam on the tumour to minimize the dose on the nearby healthy tissues

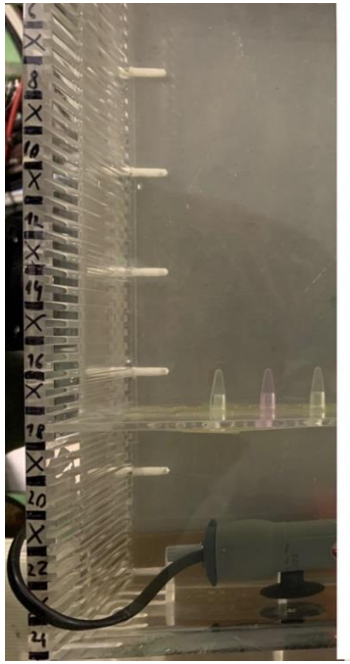
Strathclyde and Manchester

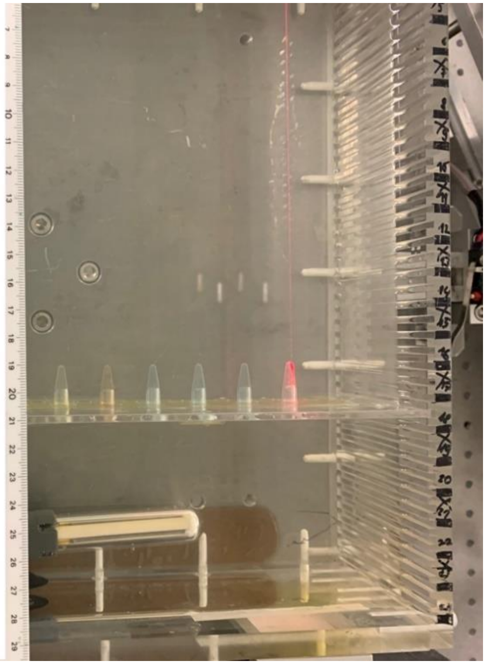


Biological effects of high dose rates









Left: dry plasmid samples on glass microscope slides.
Right: wet plasmid samples in Eppendorf tubes.
EBT-XD film placed behind samples, Manchester University
(K. Small, R. Jones et al.)

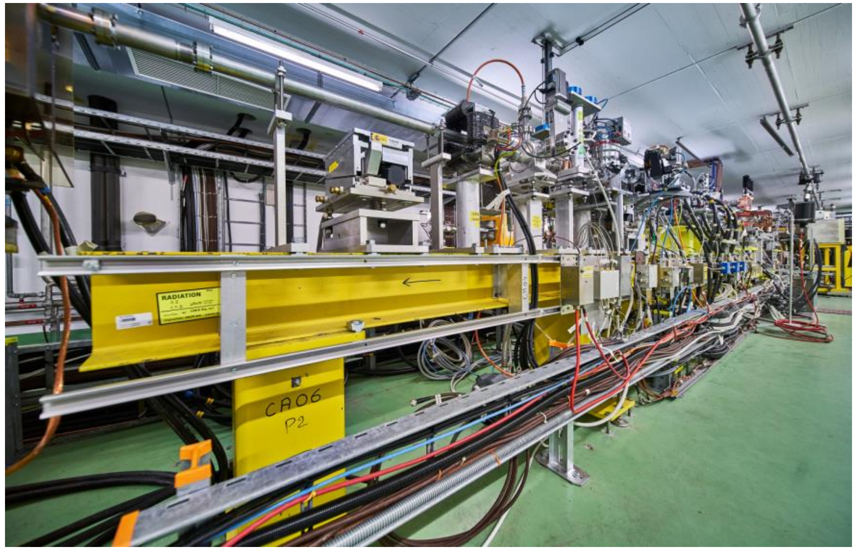
Set-up in the water tank. Zebra fish eggs, alanine pellets, gafchromic films,
CHUV Lausanne
(M.C. Vozenin, C. Bailat, R. Moeckli et al.)

VHEE in CLEAR – References

Some recent radiotherapy-related publications based on CLEAR experiments

- **A. Lagdza**, R. Jones et al., Influence of heterogeneous media on Very High Energy Electron (VHEE) dose penetration and a Monte Carlo-based comparison with existing radiotherapy modalities, Nuclear Inst. and Methods in Physics Research, B, 482 (2020) 70-81.
- **K. Small**, R. Jones et al., Evaluating Very High Energy Electron RBE from nanodosimetric pBR322 plasmid DNA damage, Nature Scientific Reports, Nature Sci. Rep. 11, 3341 (2021).
- **M. McManus**, A. Subiel, The challenge of ionisation chamber dosimetry in ultra-short pulsed high dose-rate Very High Energy Electron beams, Nature Scientific Reports (2020) 10-9089.
- **D. Poppinga** et al., VHEE beam dosimetry at CERN Linear Electron Accelerator for Research under ultra-high dose rate conditions, 2021 Biomed. Phys. Eng. Express 7 015012.
- **K. Kokurewicz**, E. Brunetti, A. Curcio et al., An experimental study of the dose distribution of focused very high energy electron (VHEE) beams for radiotherapy, Nature Commun. Phys. 4, 33 (2021).

CLEAR Operation 2022 – Some Highlights



- 20 Experiments
- About 15 User Groups internal/external
- More than 13 external collaborating institutes
- Beam from March 1st to December 12th
  (with 3 weeks summer stop)
- 40 weeks expected before shutdown

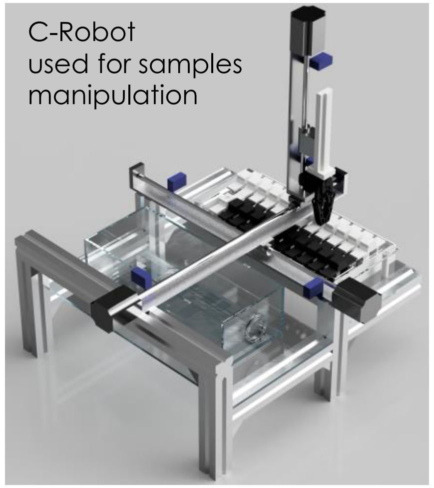
Beam Diagnostics R&D

Cherenkov Diffraction Radiation studies (beam position and bunch length monitors)

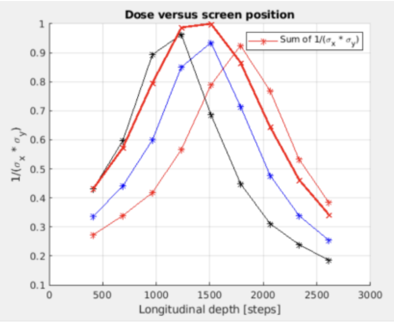
CLIC high resolution BPMs

Beam Profiler detector for the LUXE experiment

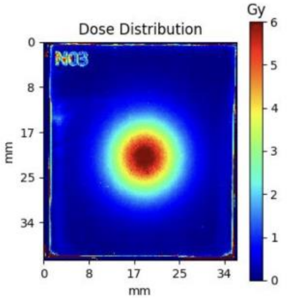
Medical Applications



C-Robot used for samples manipulation



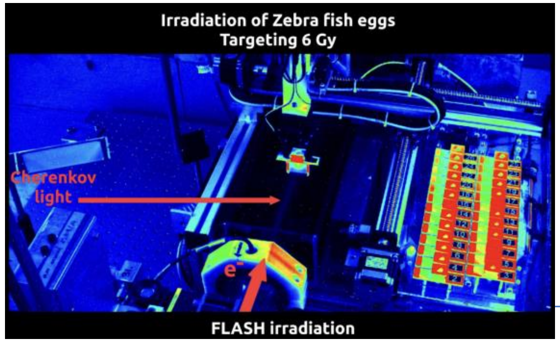
Use of focused beams for Radiotherapy (localized dose deposition)



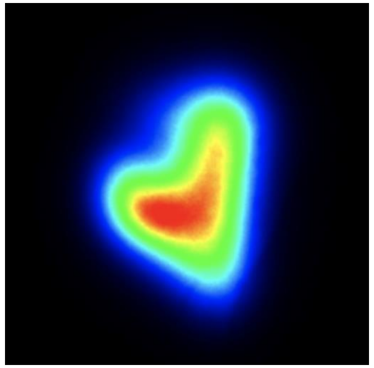
Ultra-High Dose Rate (FLASH) dosimetry: Films, Alanin, Fibers…

Chemistry and Biology FLASH experiments

H_2O_2 production – Plasmids – Zebra Fish Eggs



Thanks for your attention!



CLEAR scientific output

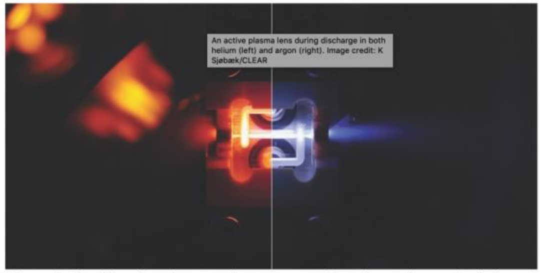
- 24 scientific papers published
  - 14 on peer-reviewed Journals, 10 in Conference Proceedings

- Many oral presentations/posters in Conferences and Workshops
- Full documentation in: https://clear.cern/content/publications

NEWS

Plasma lenses promise smaller accelerators

30 November 2018



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

ELSEVIER

Physics Letters A

Volume 391, 5 March 2021, 127135

Diffractive shadowing of coherent polarization radiation

A. Curcio [a], M. Bergamaschi [a], R. Corsini [a], D. Gamba [a], W. Farabolini [a], R. Kieffer [a], T. Lefevre [a], S. Mazzoni [a], V. Dolci [b], M. Petrarca [b], P. Karataev [c], K. Lekomtsev [d, c], S. Lupi [e], A. Potylitsyn [f]

Noninvasive bunch length measurements exploiting Cherenkov diffraction radiation

A. Curcio, M. Bergamaschi, R. Corsini, W. Farabolini, D. Gamba, L. Garolfi, R. Kieffer, T. Lefevre, S. Mazzoni, K. Fedorov, J. Gardelle, A. Gilardi, P. Karataev, K. Lekomtsev, T. Pacey, Y. Saveliev, A. Potylitsyn, and E. Senes

Phys. Rev. Accel. Beams **23**, 022802 – Published 10 February 2020

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

Education and Training

- PhD Thesis

  with experimental work in CLEAR

Agnese Lagzda
University of Manchester
2015-2019
Radiotherapy studies with very high energy electrons (VHEE) (50-250 MeV)
Supervisor: R.M. Jones

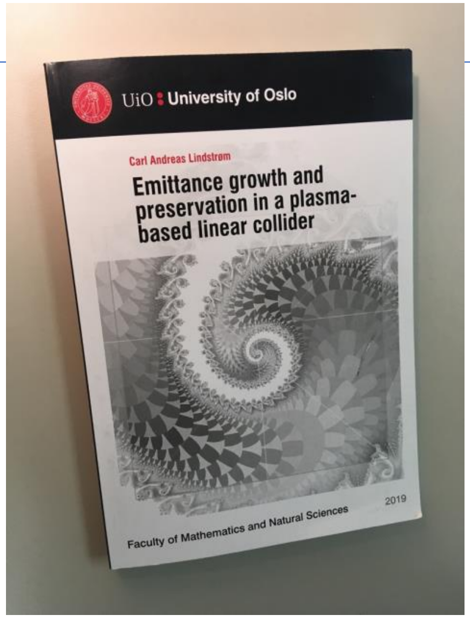
Carl A. Lindstroem
University of Oslo (Norway)
2015-2018
Emittance Growth and Preservation in a plasma-based linear collider
Supervisor: E. Adli

Maris Tali
University of Jyväskylä (Finland)
2015-2019
Single Event Radiation Effects in hardened and state-of-the-art components for space and high-energy accelerator applications
Supervisor: A. Virtanen

Antonio Gilardi
Università Federico II Napoli (Italy)
2018-2020
Measurements of impedance and wake-field with beam in linear electron accelerators: a case study at the CLEAR user facility
Supervisor: P. Arpaia

Eugenio Senes
Oxford University (UK)
2018-2020
Measuring the beam position of a low intensity picosecond long electron bunch in the presence of a high intensity nanosecond long Proton bunch
Supervisor: P. Burrows

Luke Aidan Dyks
University of Oxford
Novel acceleration technique studies in the CLEAR user Facility and its potential future upgrades
Supervisor: P. Burrows



Previous Ph.D. Thesis with experimental measurements on the CALIFES beam:

Rui Pan
University of Dundee
Bunch length monitoring using electro-optical spectral decoding
Supervisor: A. Gillespie

Michele Bergamaschi
RHUL
Emittance measurements for linear colliders using a combined OTR/ODR monitors
Supervisor: P. Karataev

Joint Universities Accelerator School

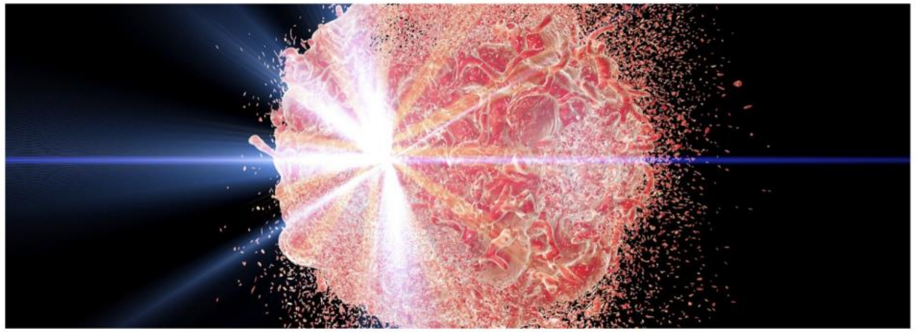
JUAS Practical Work, and also…

- Several Master Thesis
- Trainees and summer students

Recent Press Statements

News

High energy radiotherapy could 'paint' tumours to avoid harming healthy tissue

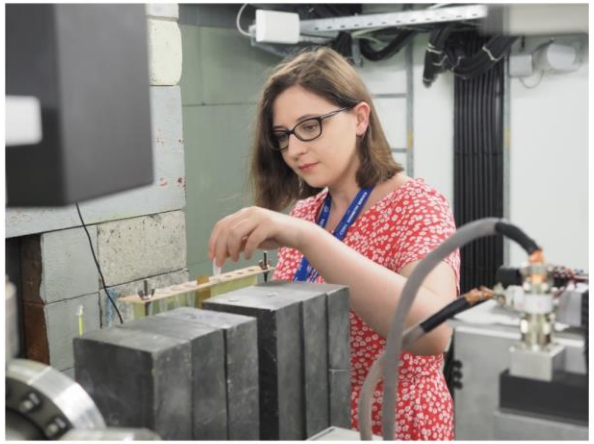


23 February 2021

A radiotherapy technique which 'paints' tumours by targeting them precisely, and avoiding healthy tissue, has been devised in research led by the University of Strathclyde.

Researchers used a magnetic lens to focus a Very High Electron Energy (VHEE) beam to a zone of a few millimetres. Concentrating the radiation into a small volume of high dose will enable it to be rapidly scanned across a tumour, while controlling its intensity.

The study was undertaken at the CERN Linear Electron Accelerator for Research (CLEAR) facility, and involved researchers at CERN, the University of Oxford, the National Physical Laboratory, the John Adams Institute for Accelerator Science, the University of Napoli Federico II, the University of Oslo and Saclay Nuclear Research Centre in France. It has been published in Nature Communications Physics.



24 February 2021

Critical step forward for radiotherapy with a new method to treat cancer

Following experiments carried out by The University of Manchester, at CERN's CLEAR 250 MeV facility and at Daresbury Laboratory, the findings show Very High Energy Electron (VHEE) beams are effective at causing DNA damage, important for killing cancer cells, for radiation given over the course of several minutes and for the rapidly evolving field of sub-second FLASH radiation.

The collaborative research team have published their findings in Nature's journal, *Scientific Reports*,