The CLEAR Facility
and Program for the Practical Days

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Outline

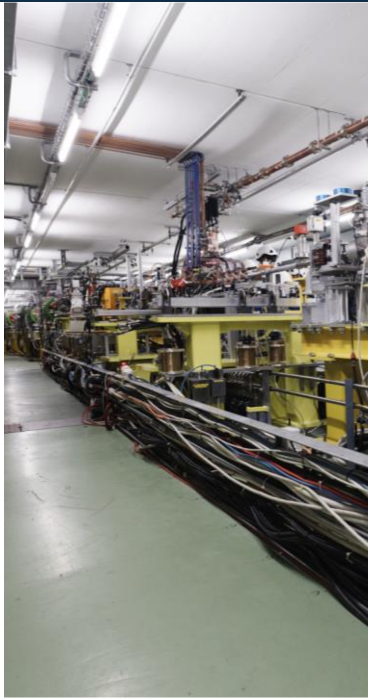
- CLEAR Beam Line: History & Parameters
- Tools and Methods used.
- Selected Medical Applications performed at CLEAR in 2023.
- Medical Applications planned at CLEAR in 2024.
- Conclusions.

CLEAR Beam Line:
History & Parameters

CLEAR Scientific and Strategic goals

Scientific and strategic goals:

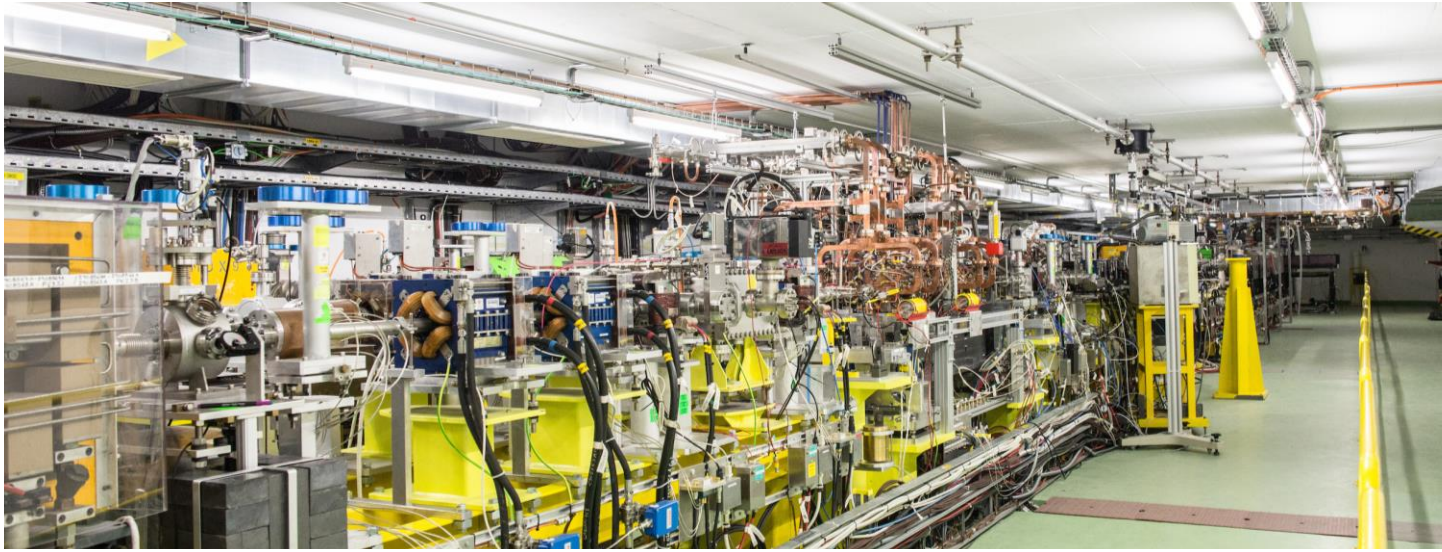
- Providing a test facility at CERN with high **availability**, easy **access** and **high-quality e-beams.**
- Performing **R&D** on **accelerator components**, including beam instrumentation prototyping and high gradient RF technology.
- Providing an **irradiation facility** with Very High Energy Electrons (VHEE), e.g., for testing electronic components in collaboration with ESA or for medical purposes.
- 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 (**including YOU!**).



CLEAR is a versatile electron linac and an experimental beamline, operated at CERN as a multi-purpose user facility.

CLEAR Timeline

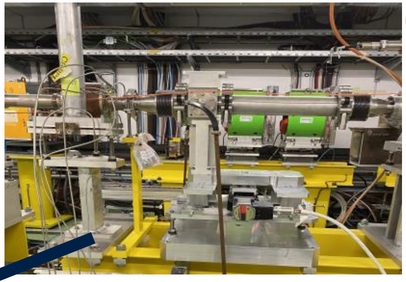
- **Approved** December 2016.
- **Began operation** in 2017.
- **Flexible** beam program.
  - 8-12 hours a day.
  - 5 days a week.
- **Independent** of LHC runs and long shutdowns.
- **2017** → 19 weeks of beam.
- **2018** → 36 weeks of beam.
- **2019** → 38 weeks of beam.
- **2020** → 34 weeks of beam (despite Covid-19).
- **2021** → 35 weeks of beam (despite Covid-19).
- **2022** → 37 weeks of beam and 27 experiments.
- **2023** → 38 weeks of beam and more than 30 experiment.



The CLEAR Beam Line in 2023

In-Air Test Stand

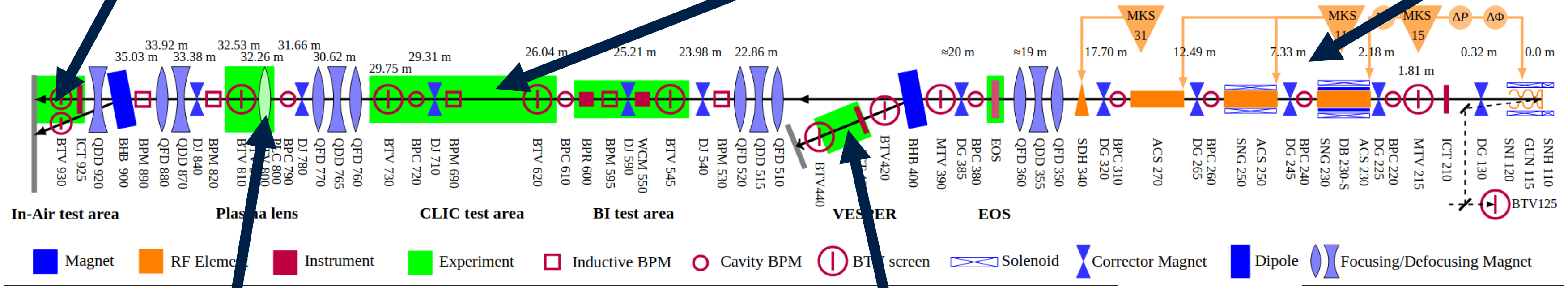
- Diagnostics studies
- Irradiation
  - Electronics
  - **VHEE**

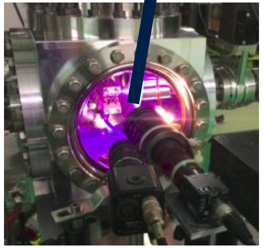


BI Test Stand

CLEAR Injector

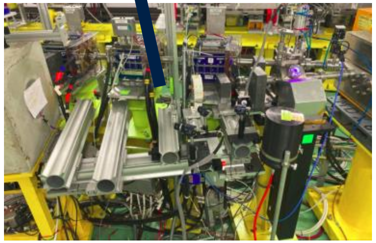
- Flexible Linac
- 60 – 220 MeV





Plasma Lens

- Novel plasma based focusing



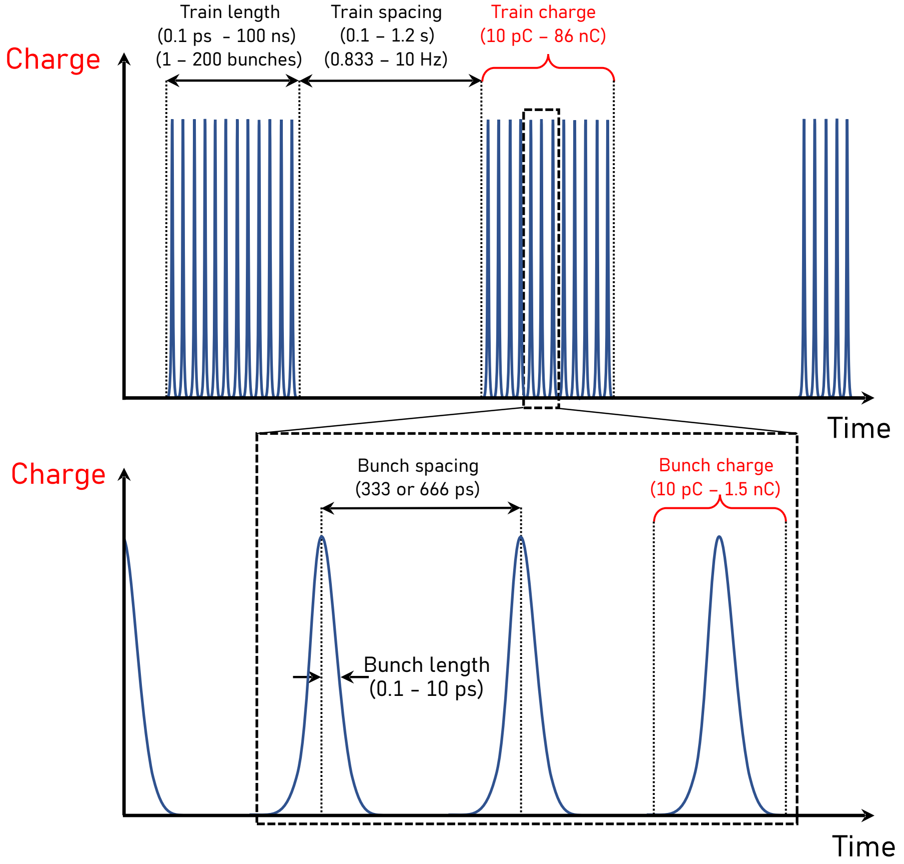
vesper

- Irradiation facility
  - Space probes
  - Electronics
  - **VHEE**

clear

CLEAR Beam Parameters in 2023

Parameter	Value
Energy	**60 – 220 MeV**
Energy spread	< 0.2 % rms (< 1 MeV FWHM)
Bunch length	**0.1 – 10 ps RMS**
Bunch charge	10 pC – 1.5 nC
Normalised emittance	3 – 20 µm
Bunches per pulse	1 – 200
Max. charge per pulse	**86 nC**
Repetition rate	**0.833 – 10 Hz**
Bunch spacing	1.5 or 3.0 GHz



What does CLEAR offer?

- Really **versatile beam parameters** (energy, size, dose, charge, length, repetition rate, position, etc.).
- **Flexible** beam program.
  - 8-12 hours a day (more, if needed).
  - 5 days a week (on the weekend, if needed).
- A **large range of existing hardware** available (C-Robot, linear stages, YAG screens, cameras, controls, etc.).
- **Numerous tools available to design and build the experiments** (milling, grinding, drilling machines, saws, 3D-printer, laser cutter, etc.).
- **Adaptive software** to remotely control the hardware and log the measured data.
- Some members of the CLEAR Operation team can help the users to **develop, design, build, install and uninstall both hardware and software** components needed for the experiment.
- **Dedicated experts** to **operate the machine and solve issues**.
- A **follow up** after the experiment to **share, filter and understand** the recorded data.

CLEAR in 2023

- **38 weeks** of beam.

- **More than 30 experiments** performed.
  Full list available on https://pkorysko.web.cern.ch/CLEAR/Table/CLEAR_experiments.html

- **More than 20 tours** of CLEAR were given in **2023** for students, artists, journalists, companies, CERN personnel…

- **CLEAR parameter ranges were increased** (beam charge, repetition rate, stability, beam size, etc.).

- **14 conference proceedings and posters**, **8 journal papers** (published or being reviewed), **9 PhD Thesis** (defended or being written) and **numerous presentations** at **workshops** and **conferences**.

- **New beam line** dedicated to **irradiations** and **medical applications** was designed and will be operational in **2025.**

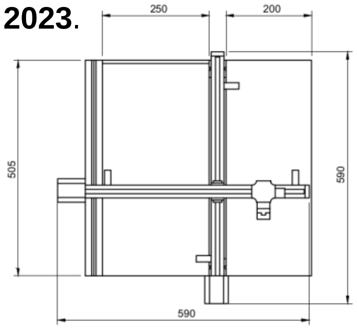
CLEAR 2023 Program

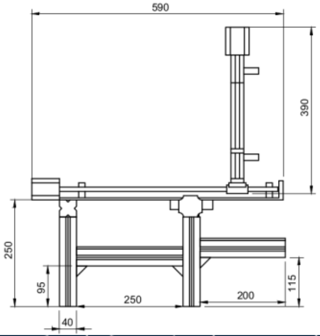
Experiment #	Experiment	Institute
1	**Joint Universities Accelerator School Practical Days**	ESI
2	**Intercomparison between 5 neutron monitors**	CERN, Politecnico di Milano, PSI, ELI-Beamlines
3	**Scintillating Fibres VHEE UHDR Real-Time Dosimetry**	University of Oxford
4	**Passive-time VHEE UHDR dosimetry**	CERN
5	**Beam Profiler detector for the LUXE experiment**	INFN Bologna
6	**VHEE Scatterers**	University of Oxford
7	**Wall Current Transformer**	Bergoz Instrumentation
8	**Plasmid Irradiations**	University of Manchester
9	**VHEE-UHDR-FLASH-RT**	CHUV
10	**Bunch Length Measurement with ChDR-EOSD**	CERN
11	**VHEE UHDR Scintillator and Biological Samples**	University of Victoria
12	**AWAKE Cherenkov Diffraction Radiation BPM**	University of Oxford
13	**Electro-Optical Spectral Decomposition**	CERN
14	**Cherenkov Light Production and Absorption in Quartz Fibers**	INFN Bologna
15	**ChDR EOSD**	CERN
16	**Bunch Profile Monitor for FCC-ee**	KIT
17	**Real-Time Beam Dose Monitors**	University of Oxford
18	**Plasma Lens**	University of Oslo
19	**VHEE Scatterers**	University of Oxford
20	**AWAKE Cherenkov Diffraction Radiation BPM**	University of Oxford
21	**VHEE Chemistry Studies**	CHUV
22	**VHEE Real-Time Dosimetry using Cuvettes**	University of Strathclyde
23	**Optical Fiber Beam Loss Monitors**	CERN/University of Liverpool
24	**CLIC Cavity Beam Position Monitors**	Royal Holloway, University of London
25	**Novel Emittance Measurements**	University of Liverpool
26	**CARE (Cable Ageing REsearch) studies**	CERN
27	**VHEE Passive & Active Dosimetry**	CERN
28	**FCC Bunch Length Monitor**	CERN
29	**VHEE Scatterers**	University of Oxford
30	**Broadband Pick-ups for the PSI Positron Production Project**	PSI
31	**microBPMs**	CERN
32	**scCVD, pCVD, Si LGADs, 3D Si sensors, 3D Diamonds Detectors**	The University of Kansas
33	**In-Vitro Radiation Sensitivity Studies of Normal and Tumour Cells**	CHUV
34	**Real-time VHEE UHDR Dosimetry**	University of Oxford
35	**AWAKE Spetrometer Scintillator Screen**	University College London

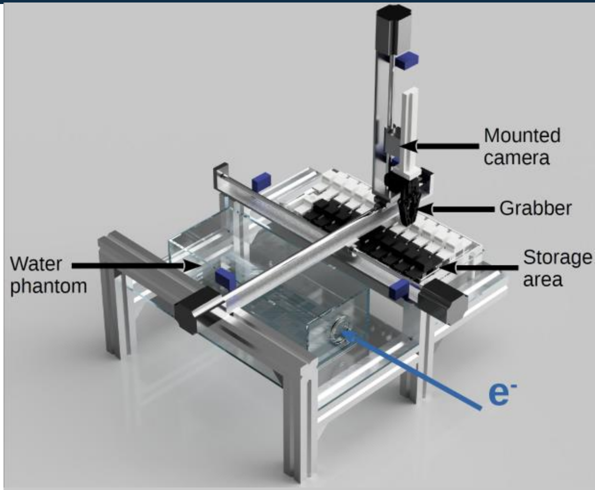
Tools and Methods

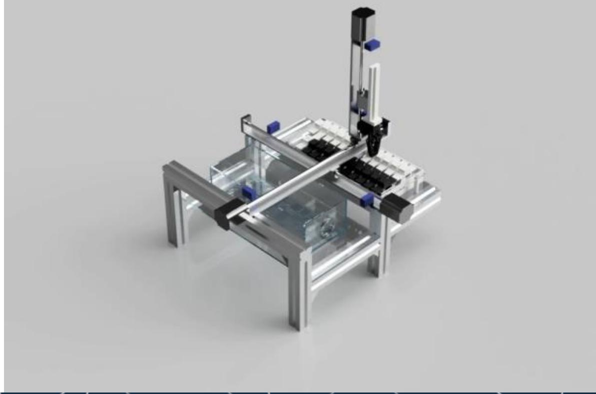
The C-Robot

- 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**.



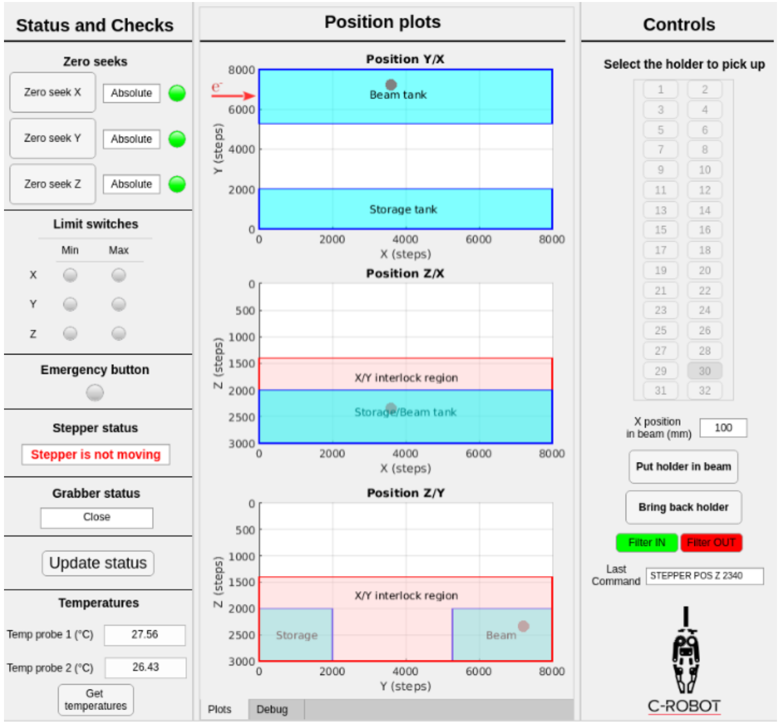




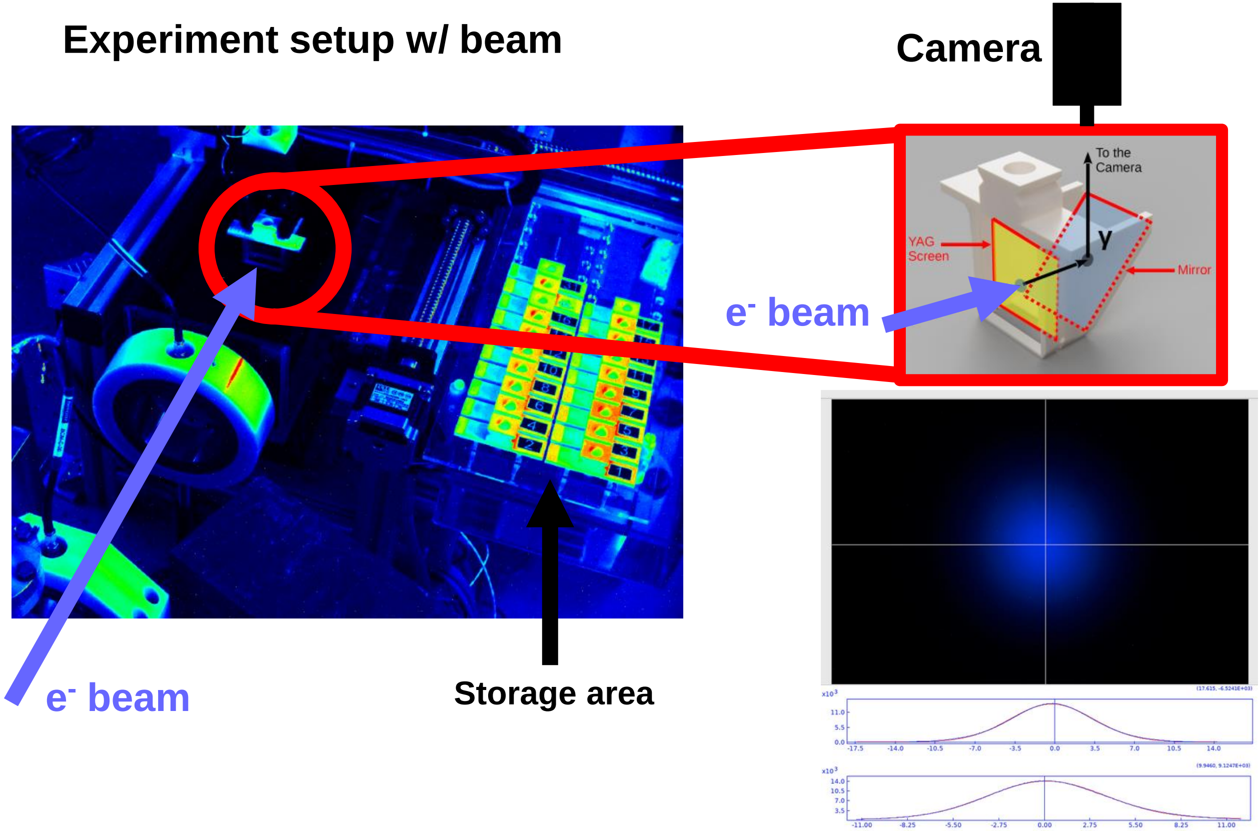


What can the C-Robot do?

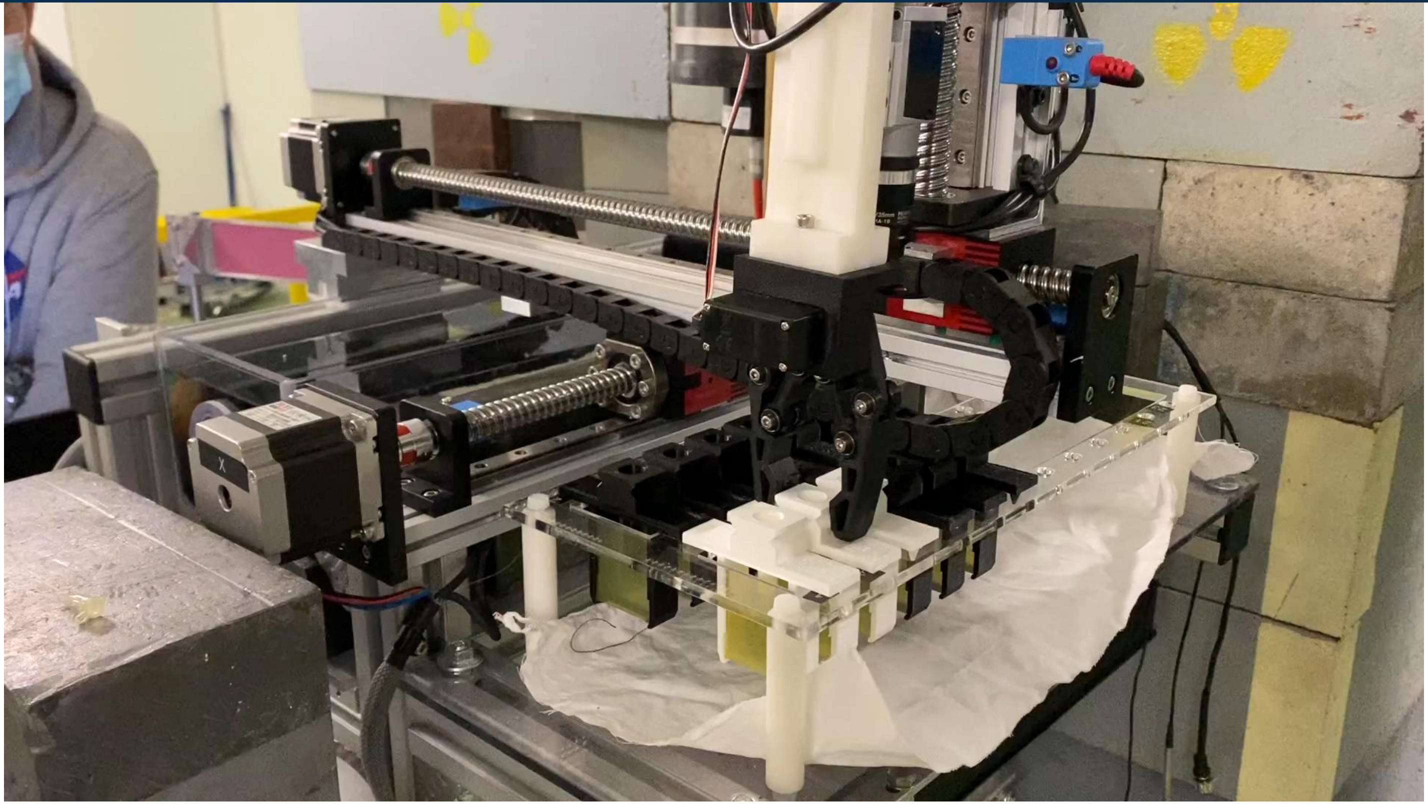
Graphical User Interface



Experiment setup w/ beam

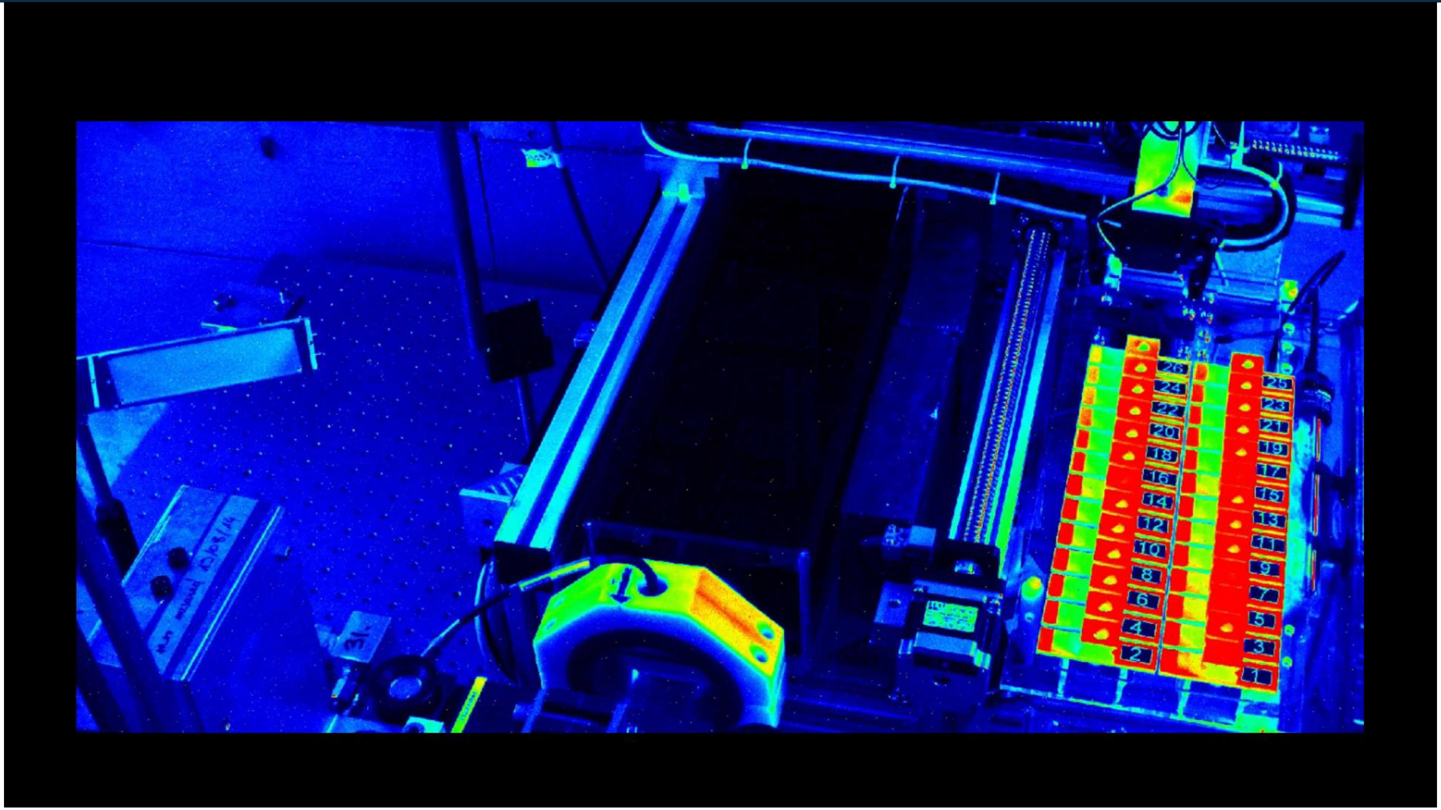


The C-Robot in action in CLEAR



Link to Video

The C-Robot in action with beam

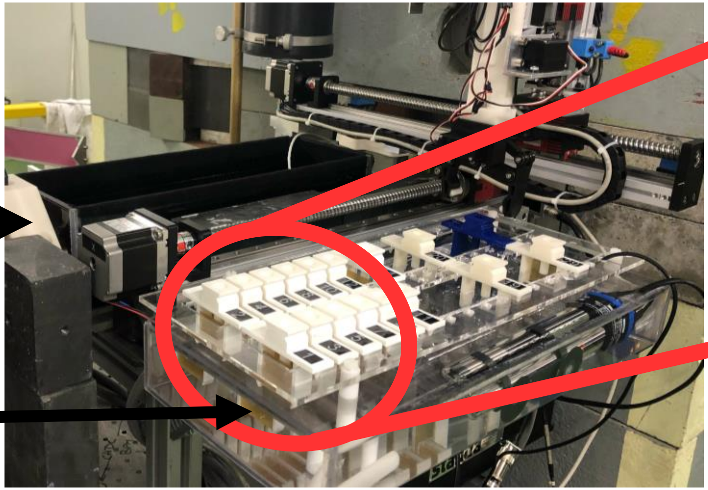


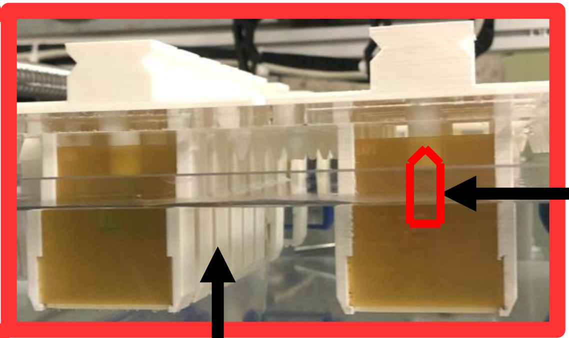
[Link to Video]

Experimental Setup & Dosimetry for VHEE at UHDR irradiations

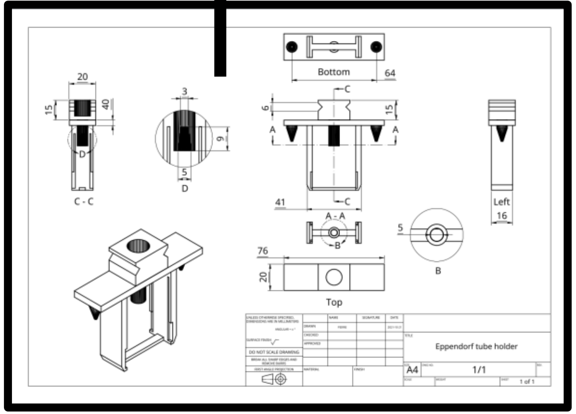
Beam water tank

Heated storage water tank





Eppendorf tube with sample to irradiate



3D printed holder with 2 films: one before and one after the sample

Laser cut Radiochromic films to measure the delivered dose

Dose range: 1 – 100 Gy

Before irradiation

After irradiation

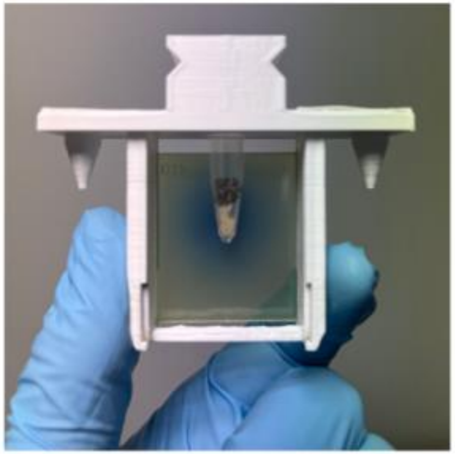
V. Rieker

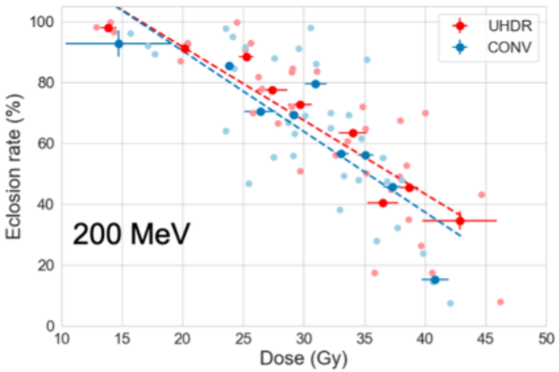
Selected Experiments performed at CLEAR in 2023:

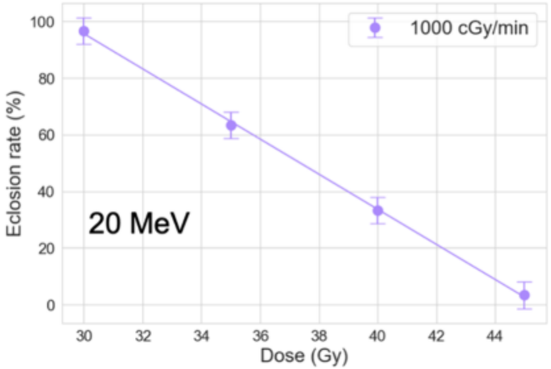
In vivo radiobiology at UHDR

Goal:
Compare the impact of 200 MeV VHEE irradiations at UHDR and CDR on *Drosophila melanogaster larvae*.

Experiment:
Deliver 15 to 45 Gy at UHDR and CDR to larvae with VHEE and measure the eclosion rate.



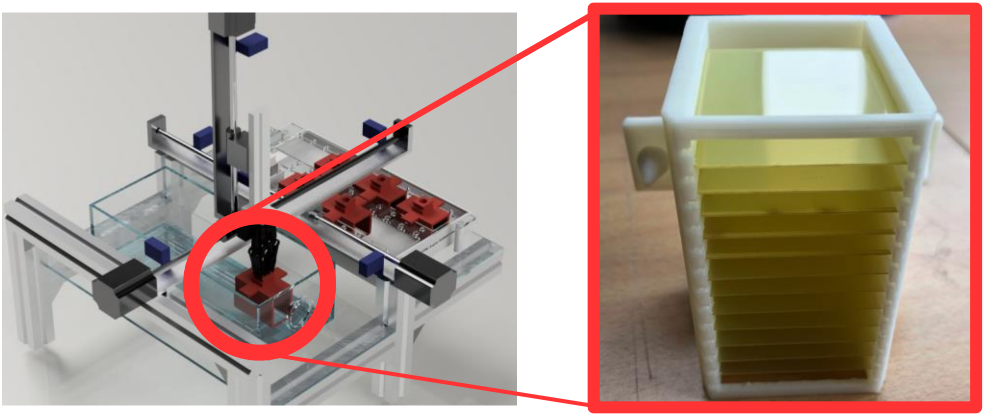


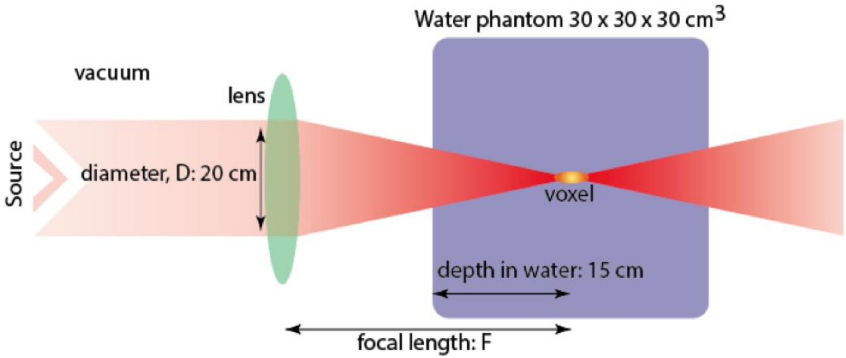


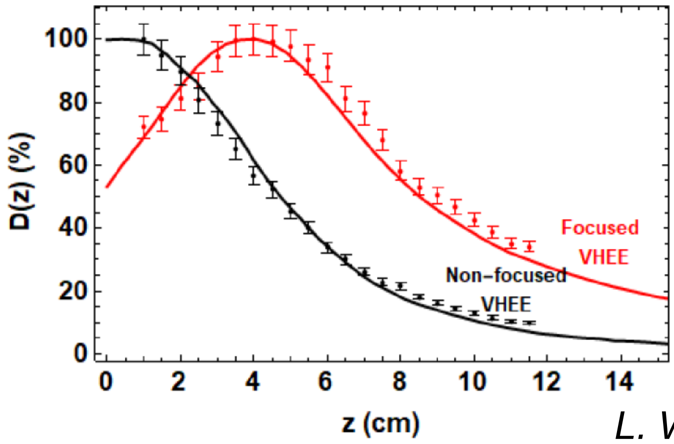
A. Hart & T. Esmangart de Bournonville

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 on a YAG screen in the water phantom (good model of the human body) and perform irradiations on long dosimetry films holders placed at different longitudinal positions.





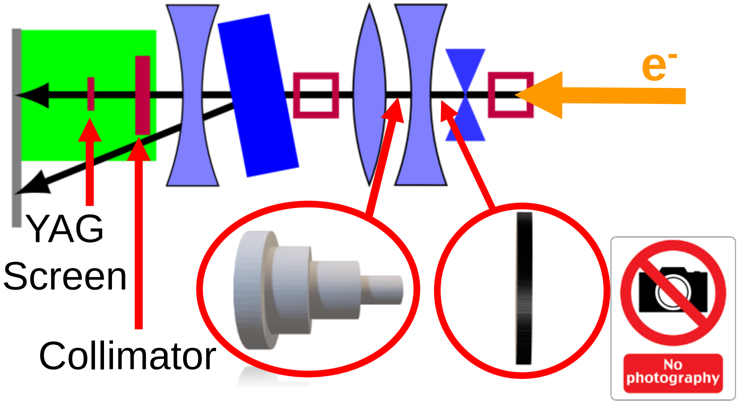


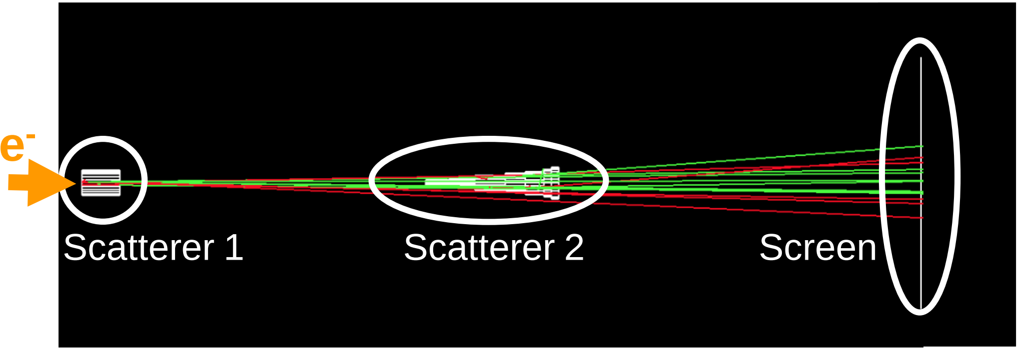
L. Whitmore

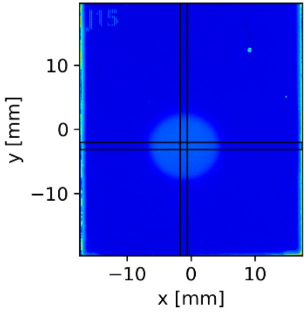
VHEE Scatterers

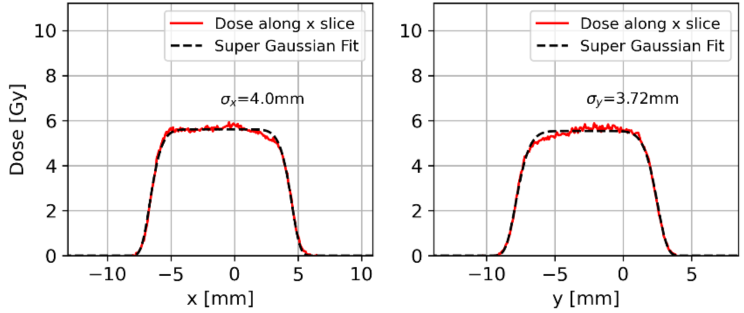
Goal:
Obtain a flat beam that has a constant transverse distribution at patient’s tumor in order to minimize the dose and damage on the nearby healthy tissues.

Experiment:
Measure beam profiles, sizes and intensity on a YAG screen and films after carefully inserting two scatterers with the beam with the C-Robot.









X and Y beam profile

C. Robertson

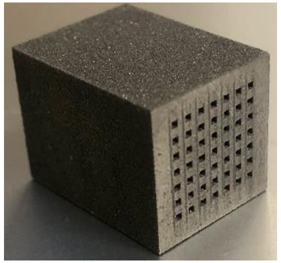
VHEE GRID

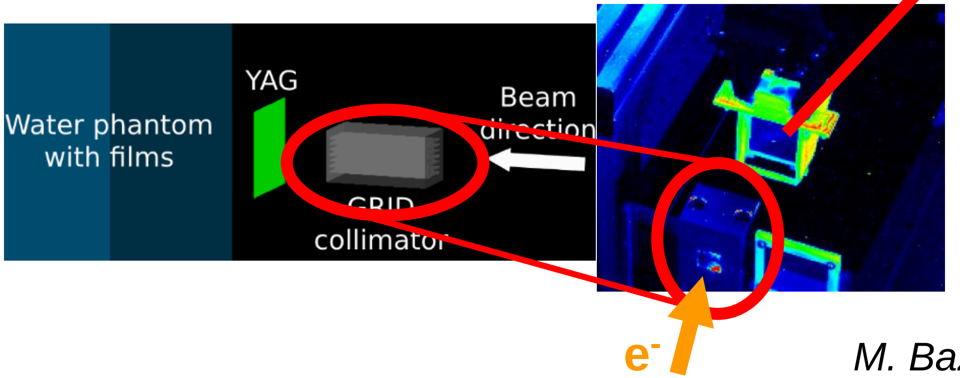
Goal:

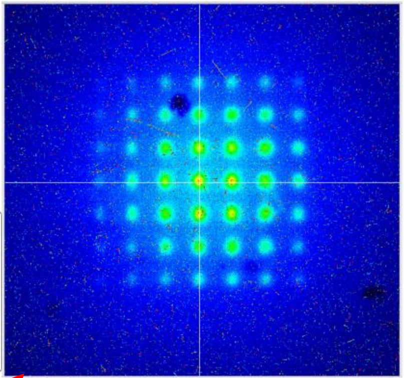
Study the dose at UHDR for highly non-uniform dose distributions using a GRID Collimator (Spatially-fractionated RT, known for normal tissue sparing).

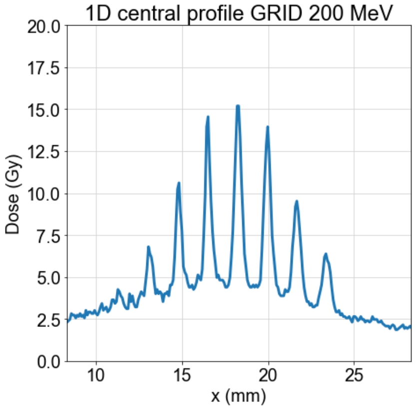
Experiment:

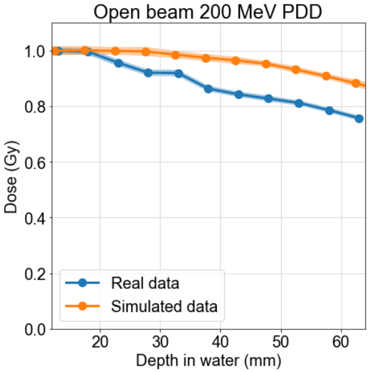
Compare the dose values and profiles with and without the GRID collimator inserted for different water depths, with the YAG screen and films.

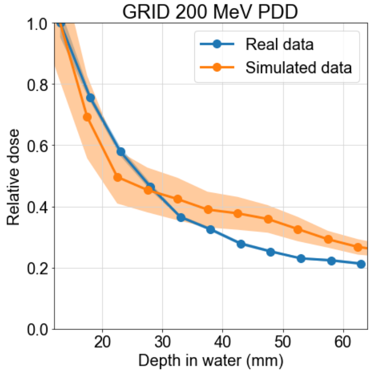












M. Bazalova-Carter, N. Clements, N. Esplen & A. Hart

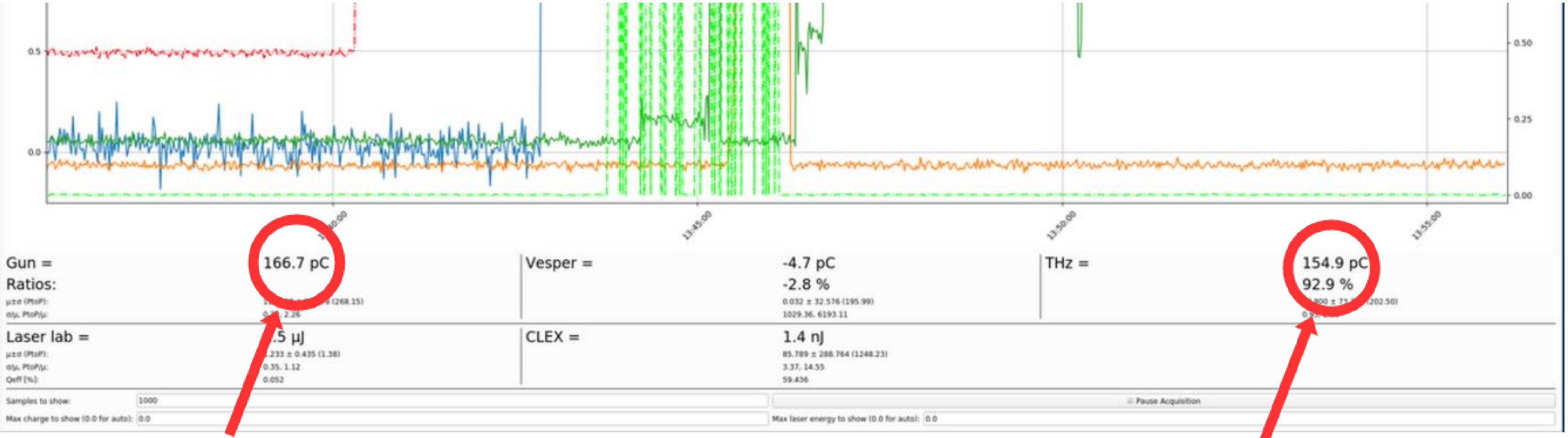
Practical Days

What will you do?

- **Transport** and **align** the beam from the electron gun to the end of the machine using the beam instrumentation devices along the line and the steering magnets.
- **Measure** the **beam energy** thanks to the spectrometer line.
- **Measure** the **beam charge** with the Integrating Current Transformers.
- **Measure** the **beam position** and **size** with scintillating screens and cameras.
- **Perform quadrupole scans** to measure the emittance and the Twiss parameters.
- **Measure** the **photo-cathode quantum efficiency**.
- **Use** the C-Robot to **irradiate samples**.
- **Operate** the accelerator from start to end.

The CLEAR Control Room

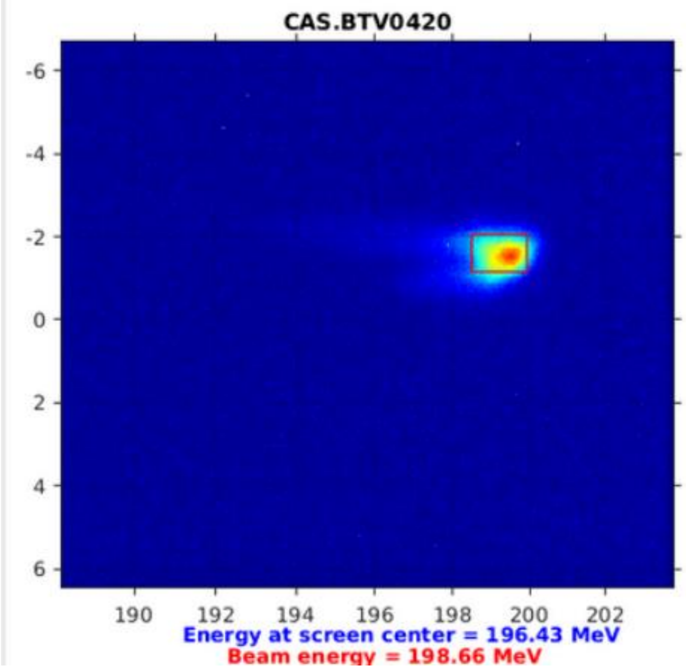
Beam charge measurement and transport



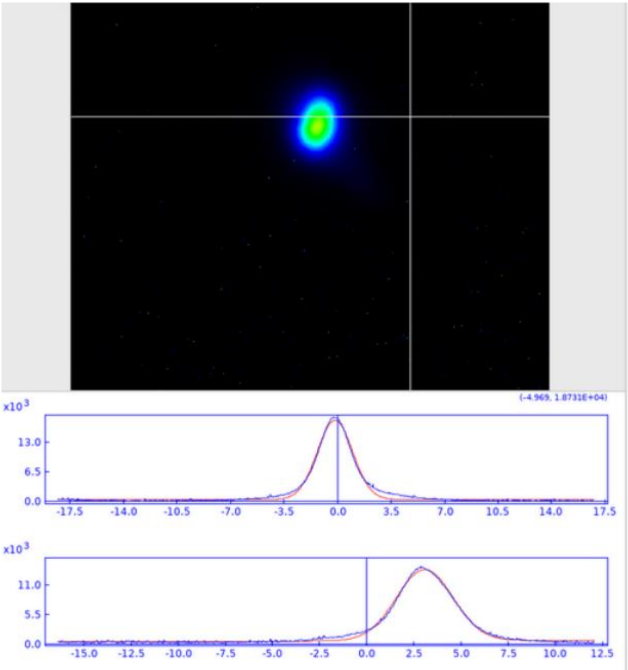
Beginning of the line:
Beam charge = 167 pC

End of the line:
Beam charge = 155 pC
Beam transport = 93 %

Beam Energy and Transverse Profile



Measurement of the beam energy with the spectrometer line (VESPER)

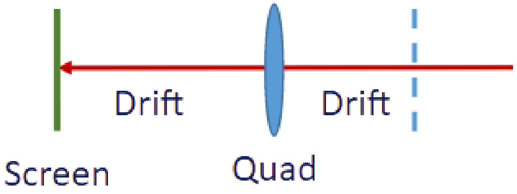


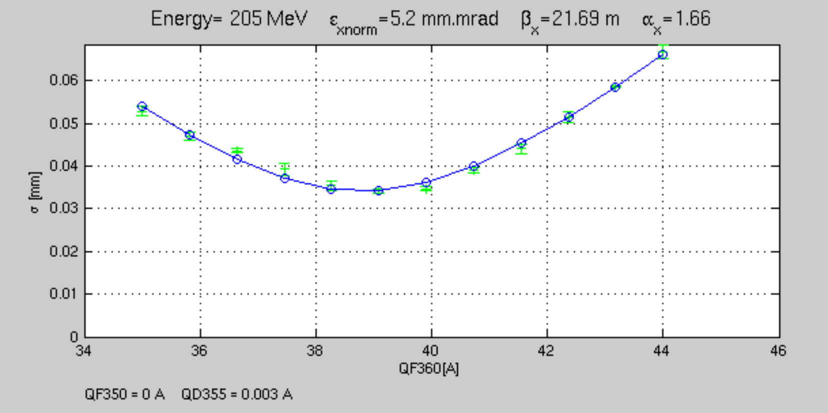
Measurement of the beam profile, position and size at the end of the line (THz)

Quadrupole Scans

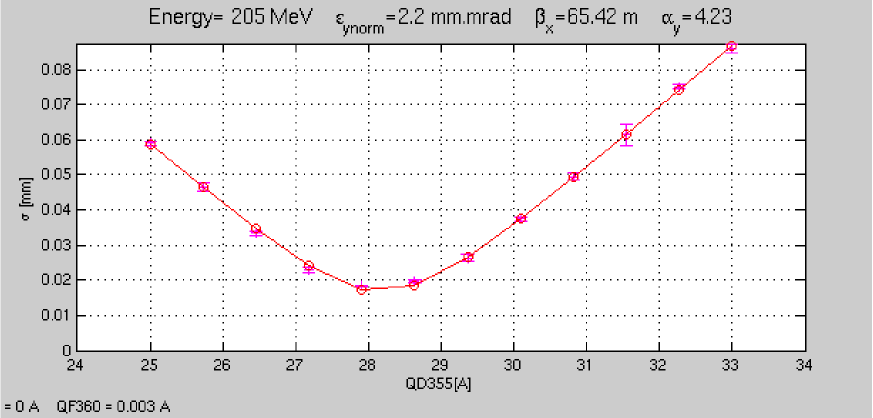
$$\begin{pmatrix}\beta_s & -\alpha_s\\ -\alpha_s & \gamma_s\end{pmatrix} = \begin{pmatrix}A_{0S} & B_{0S}\\ C_{0S} & D_{0S}\end{pmatrix}\begin{pmatrix}\beta_0 & -\alpha_0\\ -\alpha_0 & \gamma_0\end{pmatrix}\begin{pmatrix}A_{0S} & C_{0S}\\ B_{0S} & D_{0S}\end{pmatrix}$$

$$\begin{pmatrix}\beta_{s,1}\\ \beta_{s,2}\\ \vdots\\ \beta_{s,n}\end{pmatrix}\epsilon = \begin{pmatrix}A_1^2 & -2A_1B_1 & B_1^2\\ A_2^2 & -2A_2B_1 & B_2^2\\ \vdots & \vdots & \vdots\\ A_n^2 & -2A_nB_n & B_n^2\end{pmatrix}\begin{pmatrix}\beta_0\\ \alpha_0\\ \gamma_0\end{pmatrix}\epsilon$$



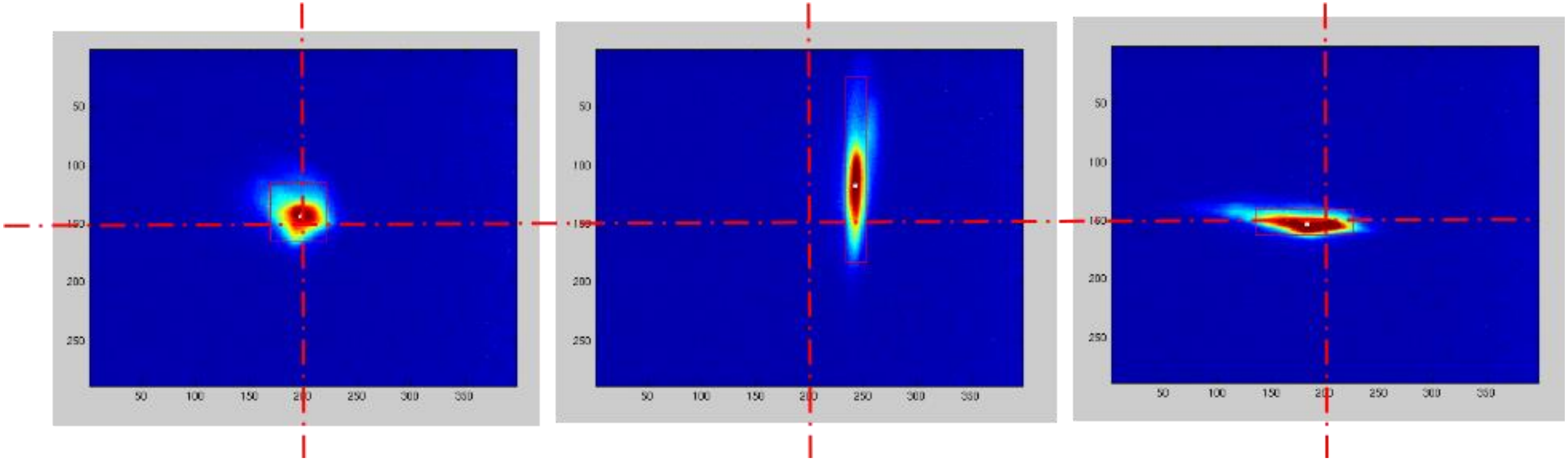


Horizontal beam size as a function of the quadrupole current



Vertical beam size as a function of the quadrupole current

Alignment of the beam in the quadrupoles

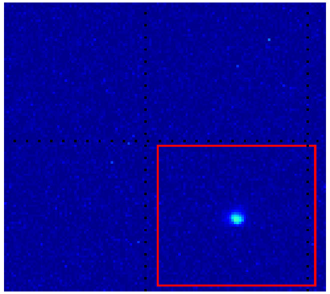


Quads Off

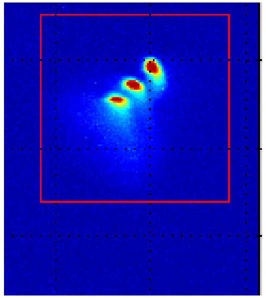
Horizontal focusing quad with beam offset in both axis

Vertical focusing quad with Horizontal beam offset

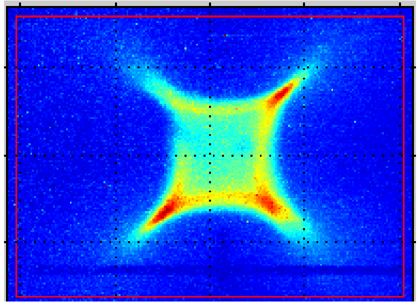
Beam Shape Contest:
Take part !



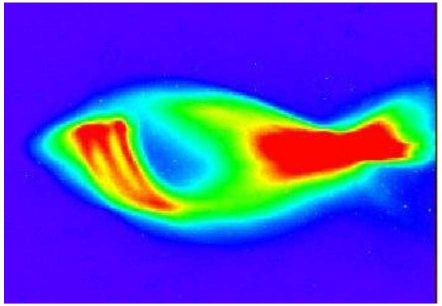
Smallest beam:
37 um x 33 um



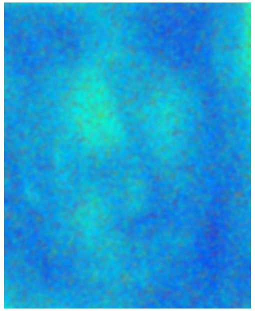
3 bunches with transverse space separation



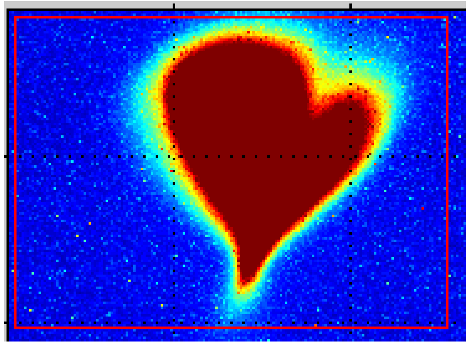
Octupolar fields



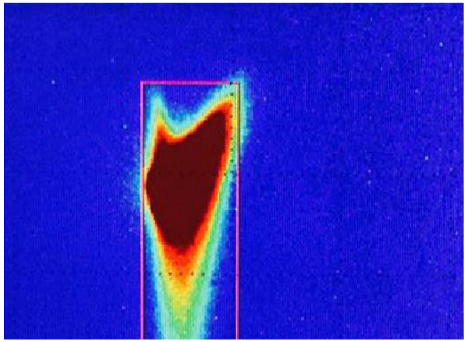
Fishy Beam



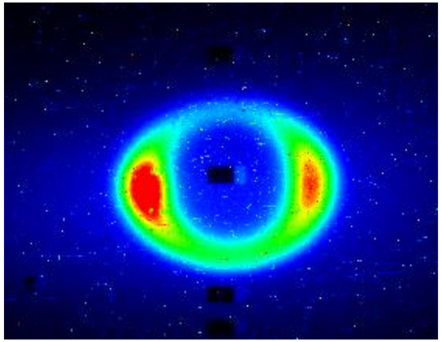
Demon’s face



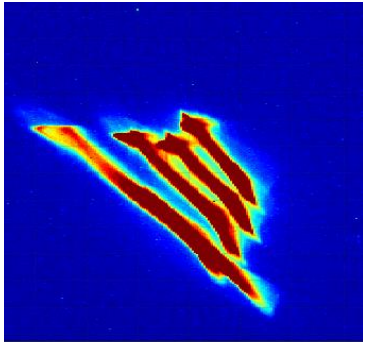
Valentine’s day beam



Cat head



« The Eye »



Monster’s claws

Thank you