ASTeC

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CLARA Commissioning and First Friendly User Experiments

Mark Johnson*, Deepa Angal-Kalinin, James Jones and Thomas Pacey, on behalf of the CLARA Team

Outline

1. Introduction to CLARA

Accelerator overview, layout, and beam parameters

2. Commissioning Highlights

Commissioning timeline and key physics measurements

3. First User Experiments

Science themes, and an overview of the experiments

Introduction

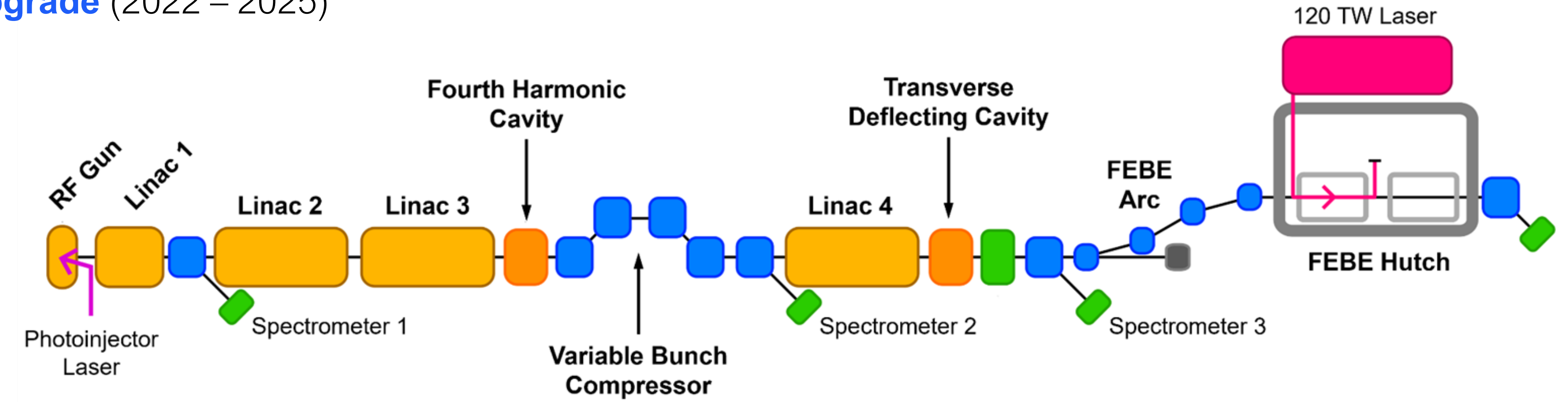
J.A. Clarke *et al.*, JINST **9** T05001 (2014)
D. Angal-Kalinin *et al.*, PRAB **23**, 044801 (2020)
E.W. Snedden *et al.*, PRAB **27**, 041602 (2024)

Science and Technology Facilities Council

- CLARA is a 250 MeV **high-brightness electron beam** facility at STFC Daresbury Laboratory (UK)
- CLARA will deliver high-quality, ultra-short electron bunches to a wide variety of **user experiments**
- The CLARA **front end** (~35 MeV) was previously operated as a successful user facility until 2022
- The accelerator has recently undergone commissioning after installation of a **major upgrade** (2022 – 2025)

Parameter	Low Charge	High Charge
Repetition Rate [Hz]	1 - 100	
Bunch charge [pC]	5	250
Bunch length [fs]	50	100
Energy spread [%]	< 1	< 5
Spot Size at IP [μm]	20	100
Norm. Emittance [μm]	2.0	5.0

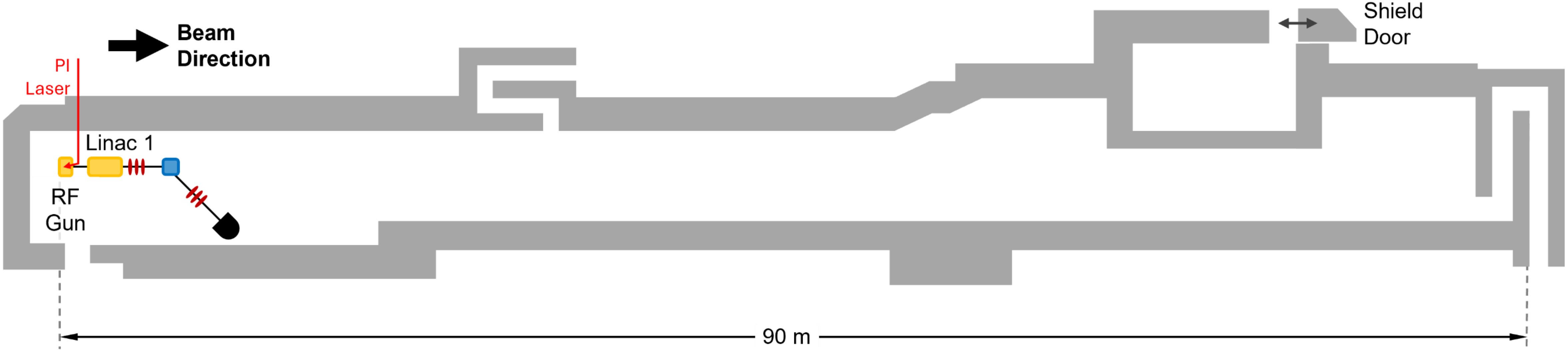
Above: Design CLARA beam parameters for user experiments
Below: Simplified schematic showing the layout of the CLARA accelerator



CLARA Front End Layout

Science and Technology Facilities Council

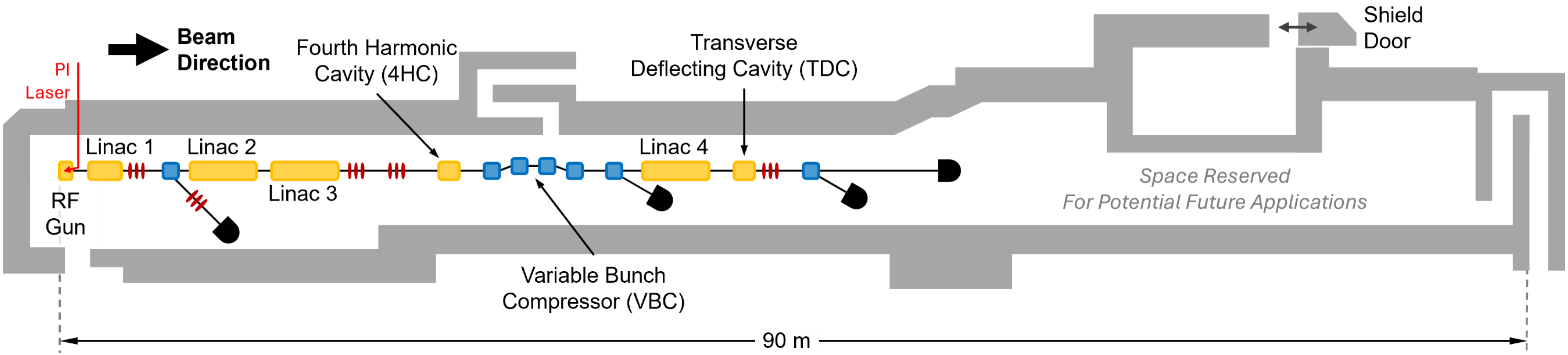
D. Angal-Kalinin *et al.*, PRAB **23**, 044801 (2020)



The **CLARA front end** was successfully operated as a separate user facility (2018 – 2022)

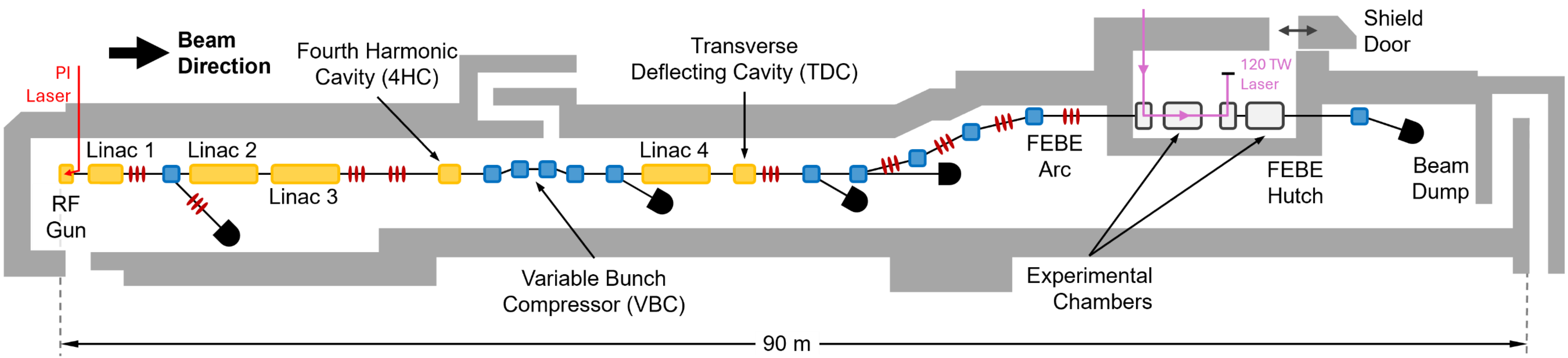
Example Technical System	CLARA Front End (35 MeV)
RF Structures	2
Magnets	22
Diagnostic Systems	13
Vacuum Gauges and Pumps	57

CLARA Layout



Example Technical System	CLARA Front End (35 MeV)	CLARA (250 MeV)
RF Structures	2	7
Magnets	22	77
Diagnostic Systems	13	65
Vacuum Gauges and Pumps	57	109

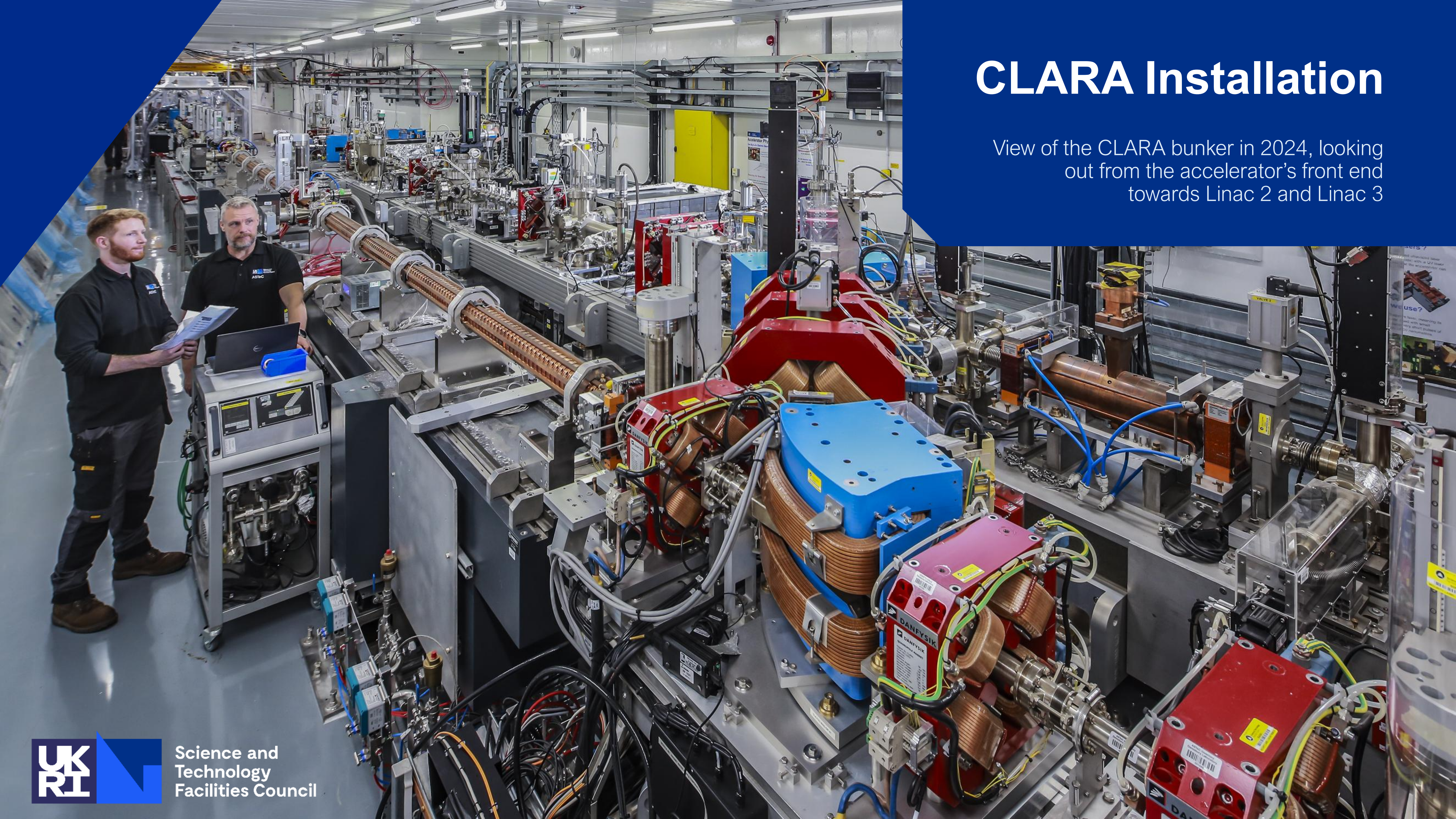
CLARA FEBE Layout



First experiments in the
Full Energy Beam Exploitation
(FEBE) user area took place
in early 2026

Example Technical System	CLARA Front End (35 MeV)	CLARA (250 MeV)	CLARA FEBE (250 MeV)
RF Structures	2	7	7
Magnets	22	77	126
Diagnostic Systems	13	65	94
Vacuum Gauges and Pumps	57	109	155

CLARA Installation



View of the CLARA bunker in 2024, looking out from the accelerator’s front end towards Linac 2 and Linac 3

Science and Technology Facilities Council

FEBE User Area on CLARA

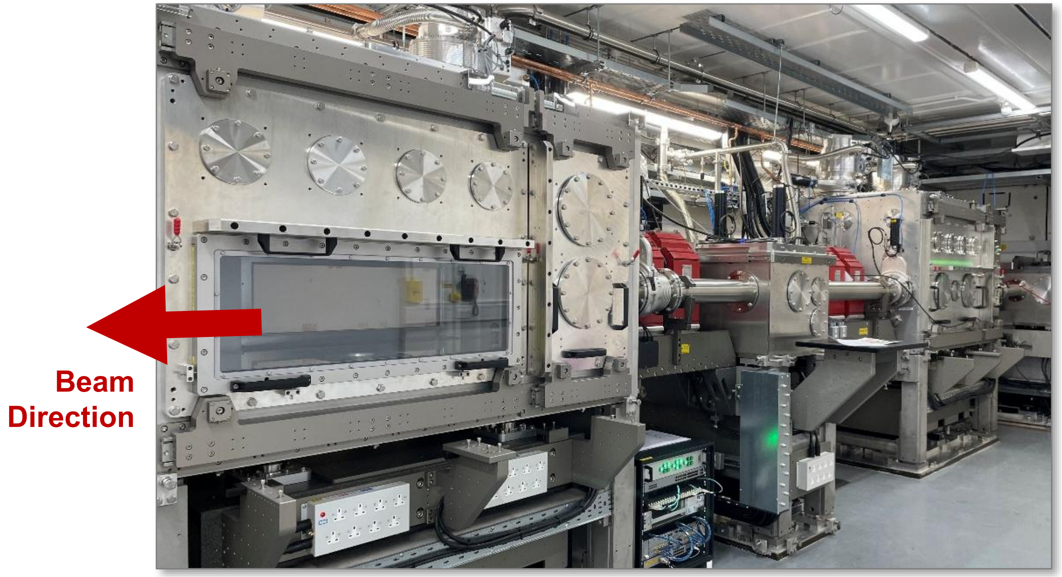
E.W. Snedden *et al.*, PRAB **27**, 041602 (2024)

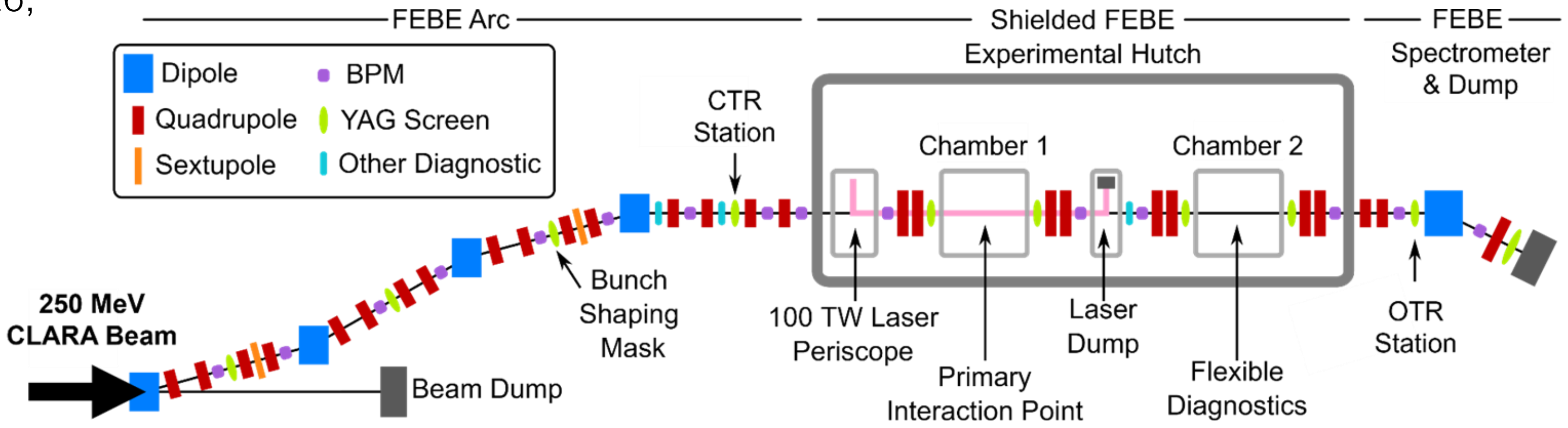
- The Full Energy Beam Exploitation (FEBE) beamline includes a dedicated user area in a **separately-shielded enclosure**

- Two large (~2 m^3) **experimental chambers** can be configured for a wide range of experiments (both in air and under vacuum):

  - ✓ Novel acceleration,
  - ✓ Advanced diagnostics,
  - ✓ New radiotherapy modalities,

- A **120 TW laser** will be available in late 2026, for applications requiring synchronized photon and electron beams





FEBE Laser System

- The FEBE laser is based on a **commercial system** (Amplitude Arco) system running at 5 Hz and 120 TW
- Combining the CLARA electron beam with high-power laser pulses will provide access to **unique experimental regimes**
- Potential **applications** include:
  - ✓ Inverse Compton scattering (ICS) studies,
  - ✓ Laser wakefield acceleration (LWFA)

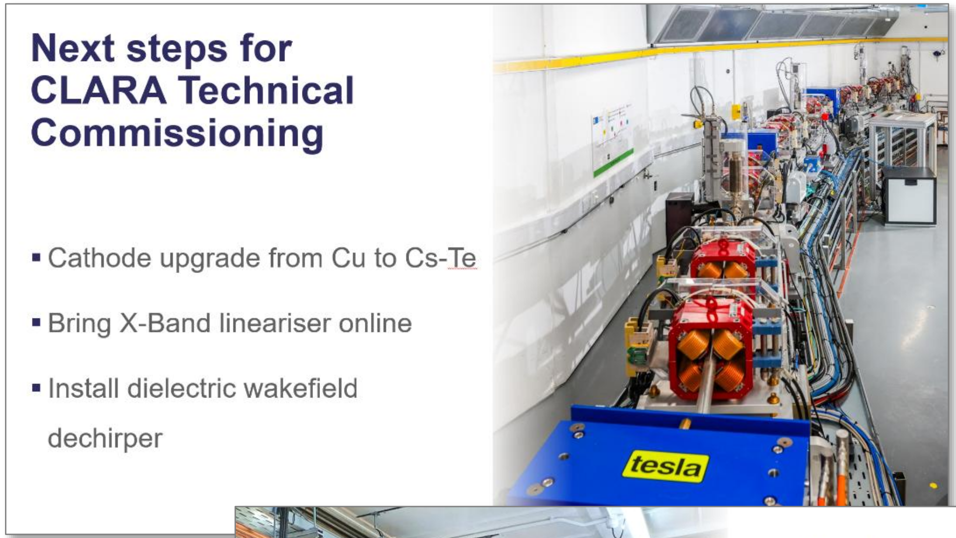
Laser transport into the FEBE area is currently being installed. Commissioning expected to be complete by **Autumn 2026**.

Laser Parameter	Value
Wavelength [nm]	800
Energy per pulse [J]	2.6
Pulse duration (FWHM) [fs]	23
Beam size at waist [μm]	30
Peak laser intensity [W cm^{-2}]	6.5 x 10^{18}
Normalised vector potential	1.75

Above: Laser system installed in a room above the FEBE hutch

Left: Estimated laser properties at the FEBE interaction point for a co-linear geometry

A Look Back…



Tom Pacey Talk
"First High Energy Beam from the CLARA Electron Accelerator and Commissioning Progress"
IOP PAB 2025

Since July 2025:

- ✅ Successful upgrade to Cs_2Te cathode
- ✅ Dielectric wakefield structure commissioned
- ✅ Extensive beam dynamics studies
- ✅ Beam transport to FEBE user area
- ❌ X-band (4^{th} harmonic) cavity delayed until Q3 2026
- ✅ First user experiments

Commissioning Timeline

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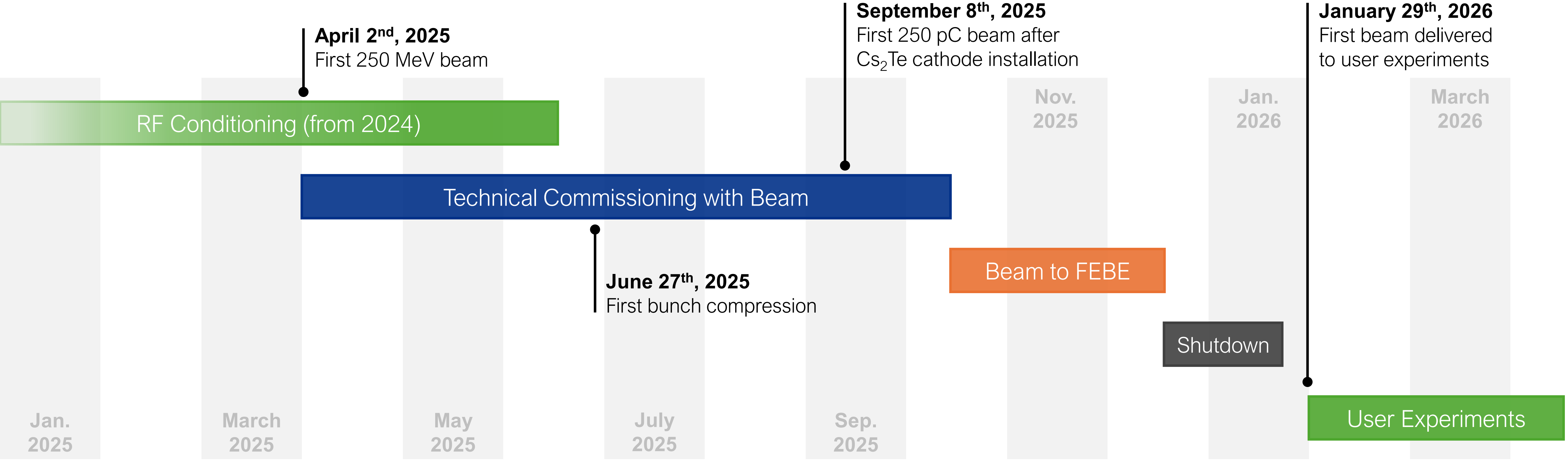
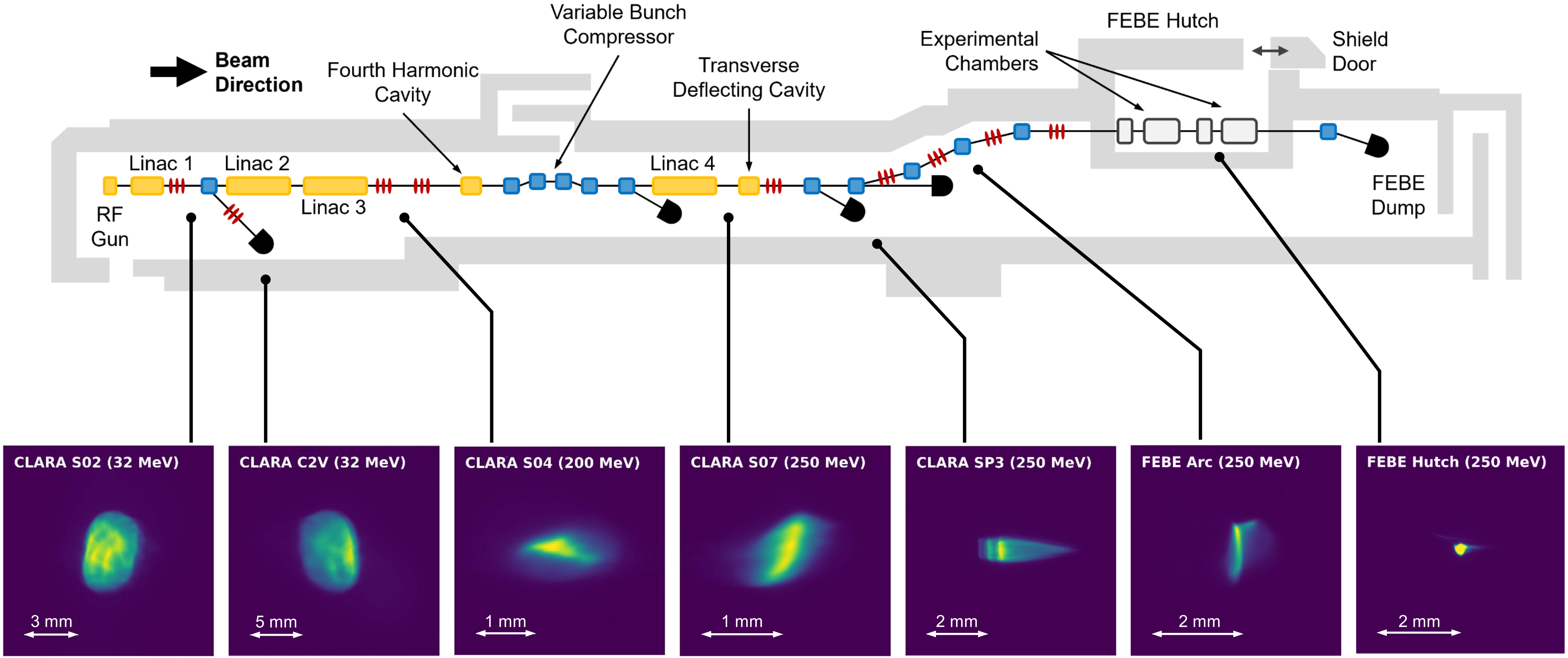
- The majority of **CLARA commissioning** was completed in 2025, often in parallel with RF conditioning and/or FEBE installation work

- A **machine development** (MD) period is currently underway, for detailed optimisation of the beam parameters



Beam Images (250 pC)



Cs_2Te Photocathodes

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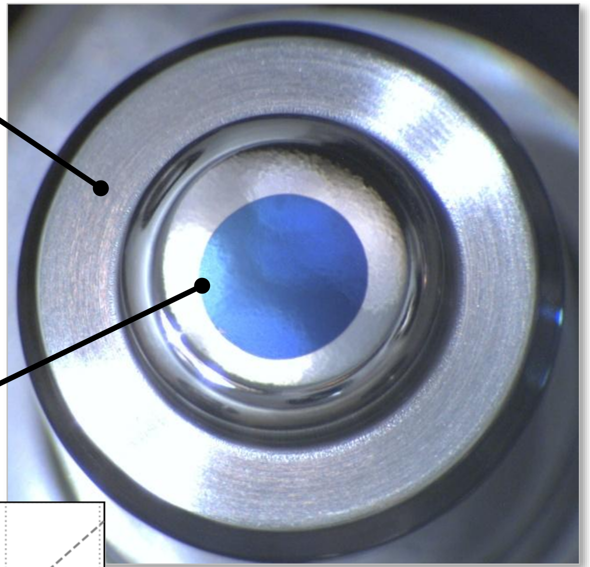
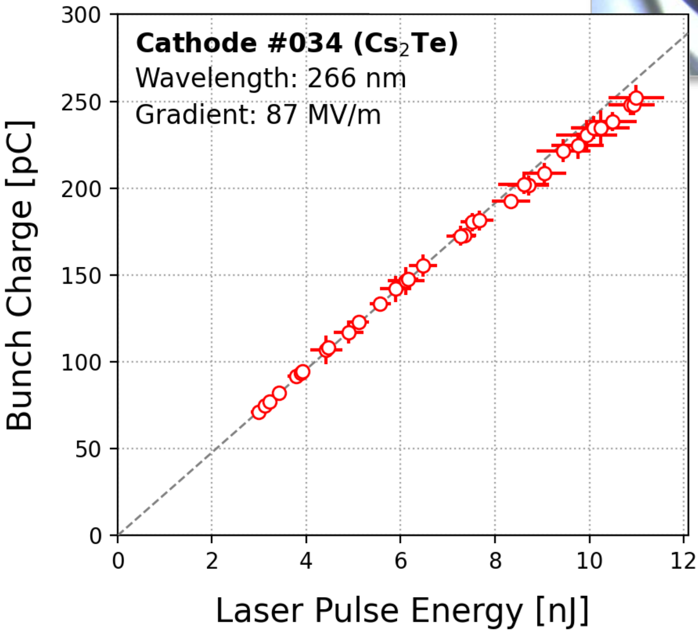
- Caesium telluride (Cs_2Te) **photocathodes** for CLARA were developed in-house at Daresbury
- Installation of the first Cs_2Te cathode (Sept. 2025) facilitated an increased **bunch charge** up to 250 pC
- Stable effective **quantum efficiency** (QE) of ~10% measured under operational conditions in the CLARA gun
- Laser energy now available for longitudinal **pulse shaping** in future





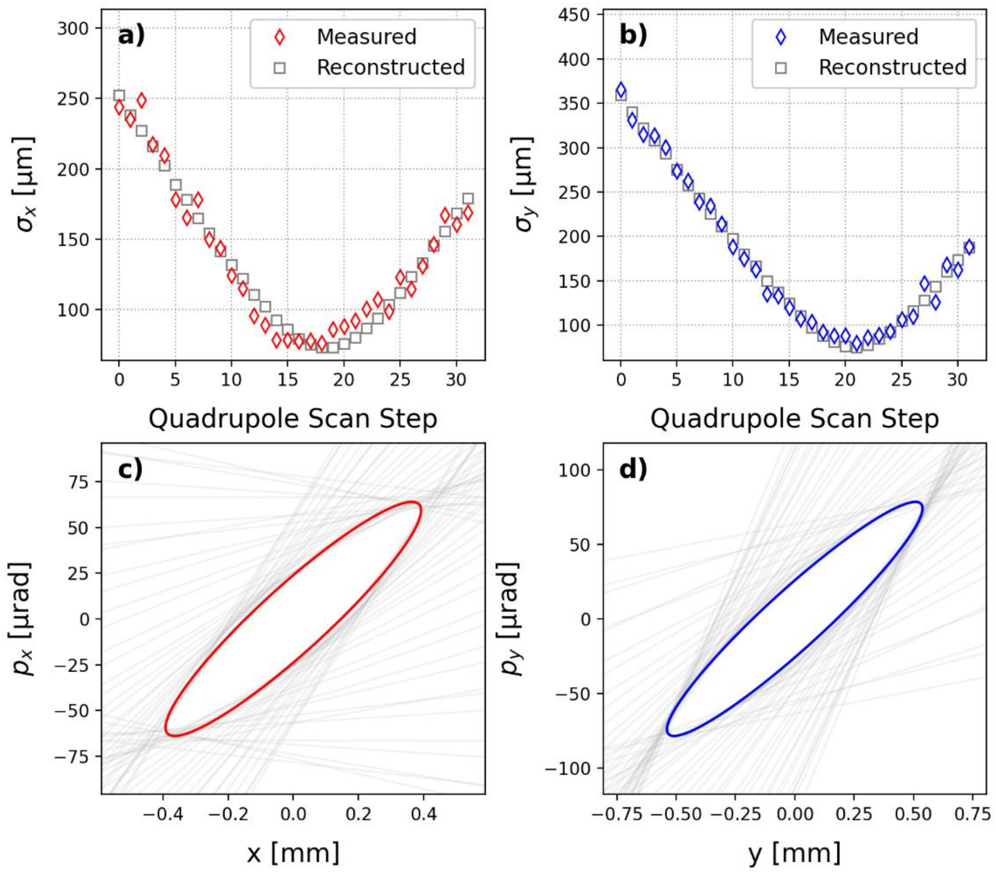
Above: Photocathode surface, with Cs_2Te coating on the active area

Left: Typical QE measurement for a CLARA photocathode

Emittance Measurements

- Emittance measurements are based on **quadrupole scans** throughout the CLARA beamline
- We routinely achieve emittances of < 1 µm in the low-energy (35 MeV) section immediately after the **CLARA injector**
- Work is ongoing to mitigate **emittance growth**, which is most likely due to transverse wakefields in the linac cavities

Beam Setup (250 pC)	Horizontal Normalised Emittance [µm]
Post-injector (35 MeV)	0.7
Uncompressed (250 MeV)	2.3
Compressed (250 MeV)	~5.0



Above: Results of a typical quadrupole scan in the low-energy section after the CLARA injector

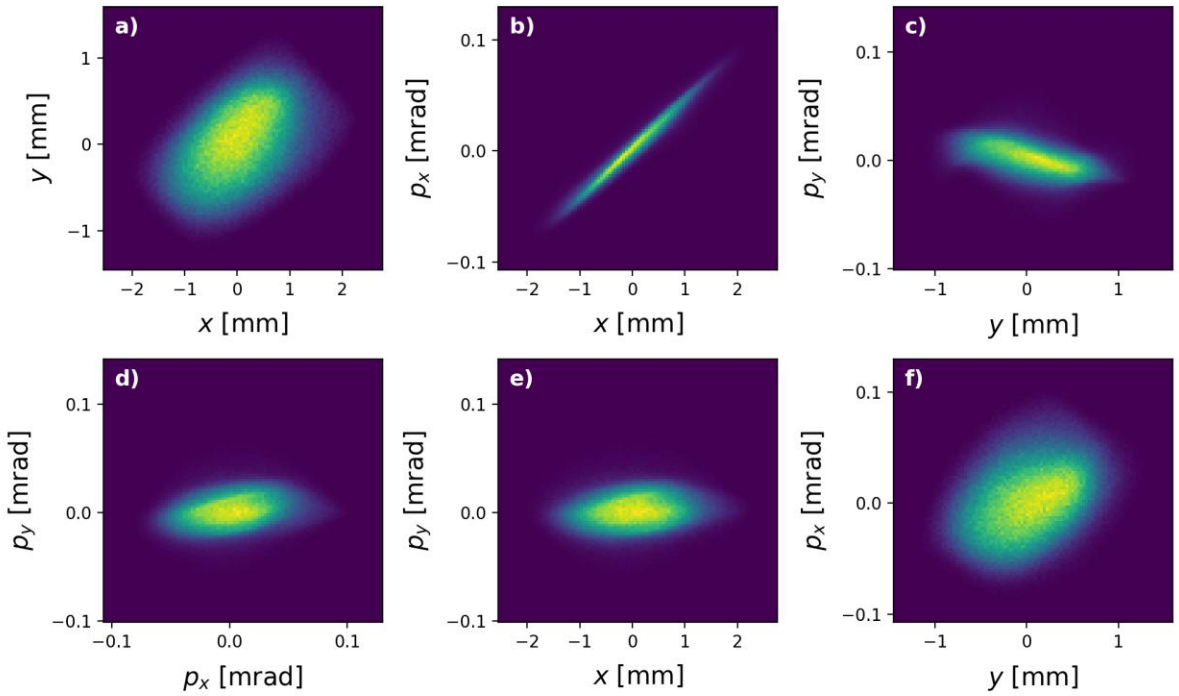
Left: Emittance measurements for a 250 pC compressed beam. High-energy measurements were made immediately after the final linac

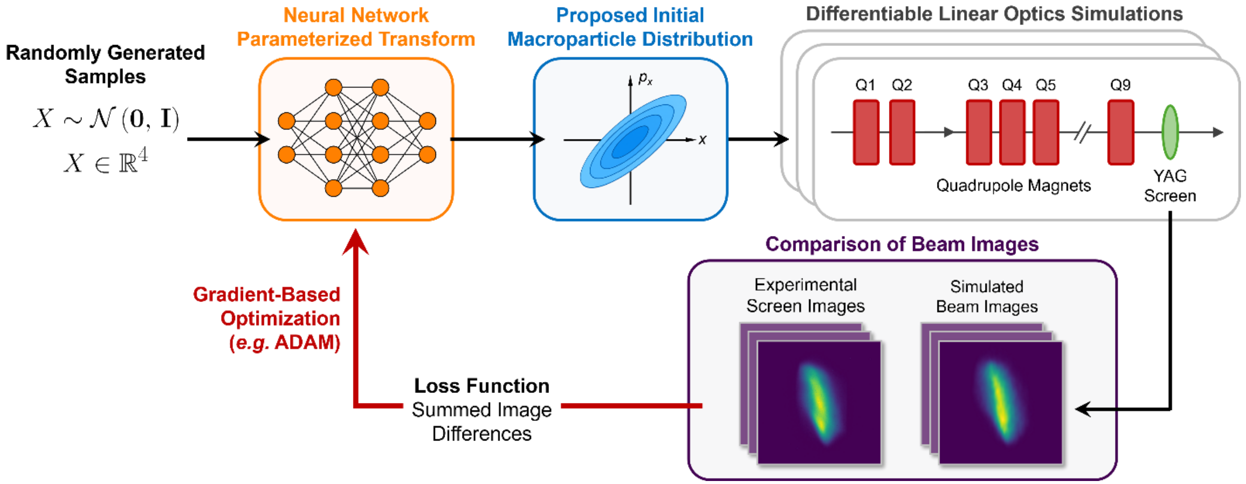
Phase Space Tomography

R. Roussel *et al.*, PRL **130**, 145011 (2023)
R. Roussel *et al.*, PRAB **27**, 094601 (2024)

Science and Technology Facilities Council

- We also use generative Machine Learning (ML) for high resolution measurements of the **transverse phase space**
- The ML technique accurately reconstructs the beam's **charge distribution**, including any substructure
- The method provides an **accurate representation** of the beam that can be used for analysis of **user experiments**



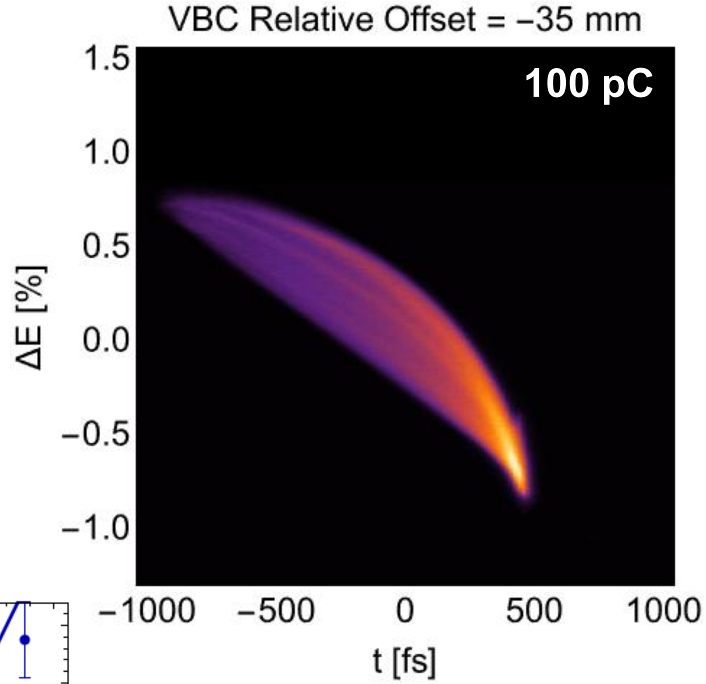


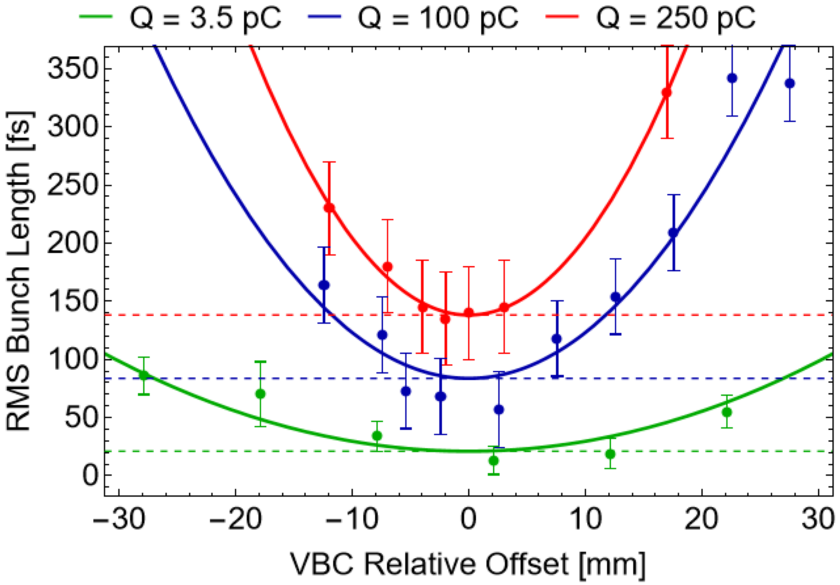
Above: 4D transverse phase space, reconstructed for an uncompressed 30 pC beam immediately after the final linac

Left: Diagram showing the generative phase space reconstruction (GPSR) method for reconstructing a charge distribution from experimental data

Longitudinal Dynamics

- The CLARA lattice allows **measurement and manipulation** of the beam's longitudinal phase space:
  - ✓ Variable bunch compressor (VBC)
  - ✓ Transverse deflecting cavity (TDC)
  - ✓ Passive dielectric dechirper
- The 250 pC CLARA beam can be compressed to a minimum RMS **bunch length** of ~150 fs
- Commissioning of the **fourth harmonic cavity** will facilitate highly compressed beam modes





Above: Animation showing measurements of the longitudinal phase space for different VBC offsets

Left: Measured RMS bunch length as a function of VBC offset

Longitudinal Space Charge

K. Yasutome *et al.*, in Proc. IPAC26, **THO3T03** (2026)

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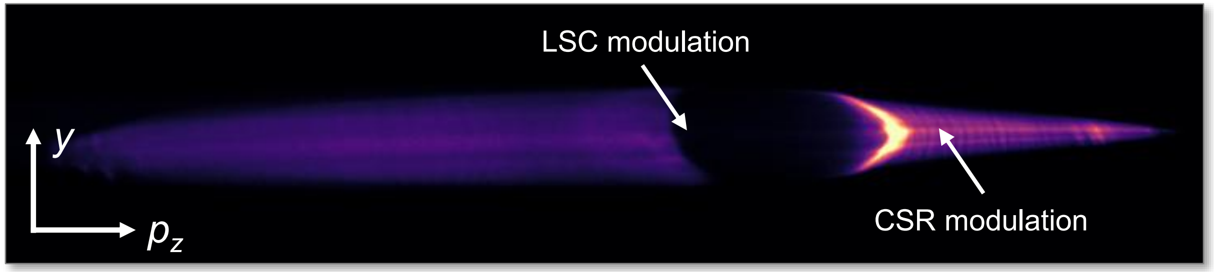
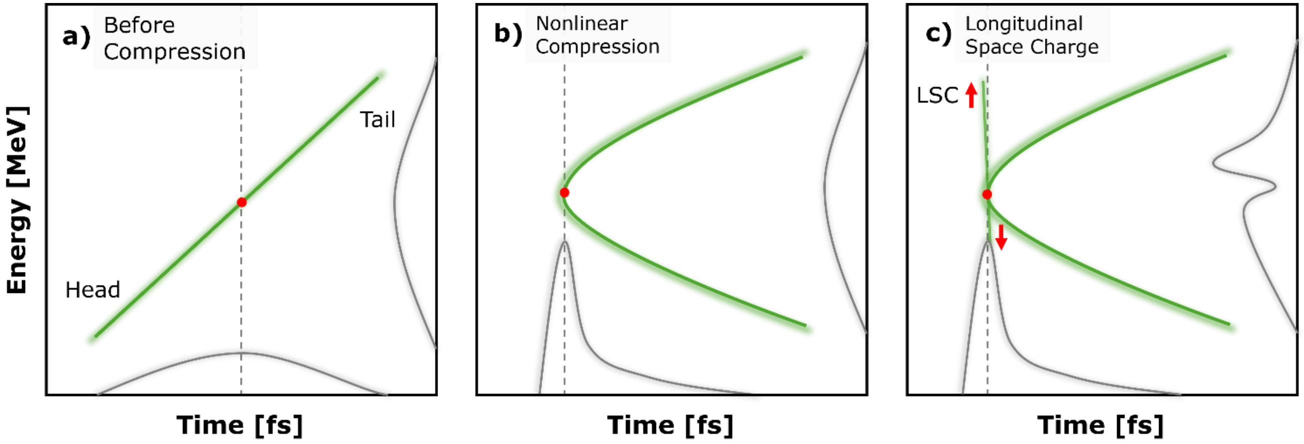
- During commissioning, we noticed a strong **modulation** of the beam **energy spectrum** near maximum bunch compression
- Recent experimental studies revealed that the effect is caused by strong **longitudinal space charge** (LSC)
- LSC is driven by a **current spike** at the head of the bunch, which forms due to its non-linear longitudinal phase space.
- The effect has been reproduced in start-to-end simulations, and can be mitigated with the **fourth harmonic cavity**

Observed at any **bunch charge** between 5 – 250 pC



Above: Spectrometer images showing the energy spectrum of the 250 MeV CLARA beam near maximum compression



Above: Simplified diagram showing the effect of LSC on the CLARA beam. Adapted from Yasutome *et al.* (2026)

Passive Wakefield Structure

T. Overton *et al.*, in Proc. IPAC26, **WEP6091** (2026)

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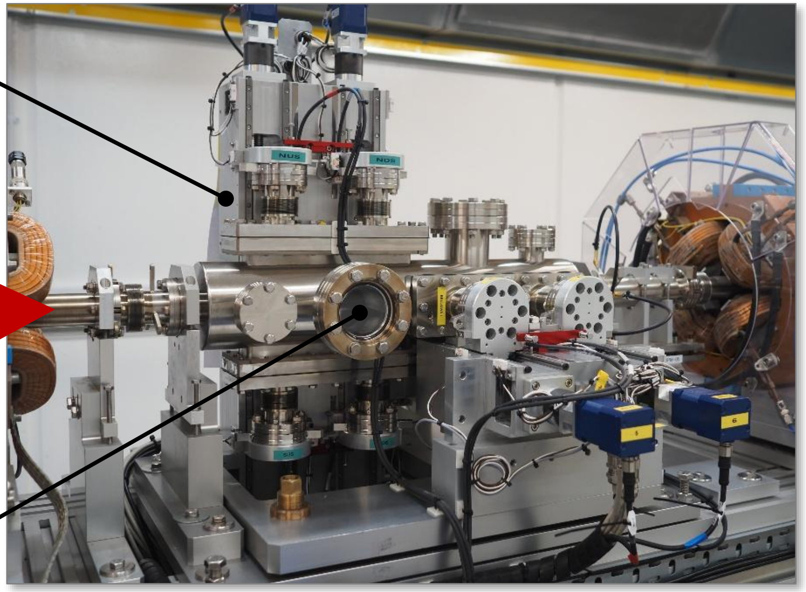
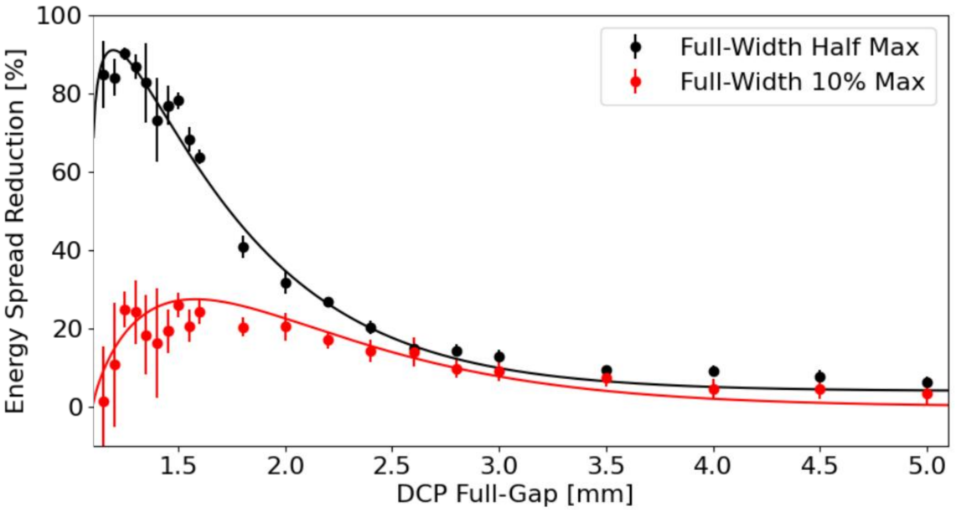
- A passive **wakefield structure** has been installed in the final section of CLARA (250 MeV/c)

- The device uses wakefields excited by the beam itself to **manipulate** the longitudinal phase space. It can be used as a:
  - ✓ **Dechirper** to remove correlated energy spread,
  - ✓ **Streaker** to infer the time structure of the bunch

- **Commissioning** of the device as a **dechirper** has demonstrated:
  - ✓ Reduction of the beam energy spread,
  - ✓ Preservation of the transverse emittance





Above: Passive wakefield structure installed on the CLARA beamline

Left: Measurements of energy spread as a function of dechirper gap, for a 250 pC beam

Beam Stability

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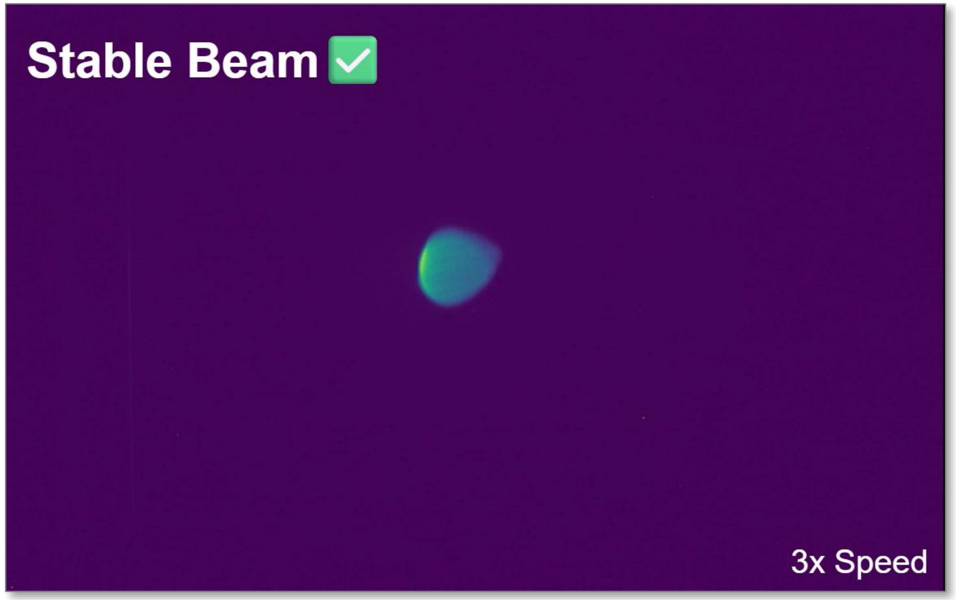
- The CLARA electron beam benefits from **stable operation** across a wide range of **timescales**:
  - ✓ Shot-to-shot jitter (10 - 100 Hz),
  - ✓ Recovery from an RF trip (seconds)
  - ✓ Slow drifts (minutes to hours),
  - ✓ Reproducibility between shifts (days)
- Multiple CLARA users gave **feedback** indicating that their experiments would not have been possible without this stability



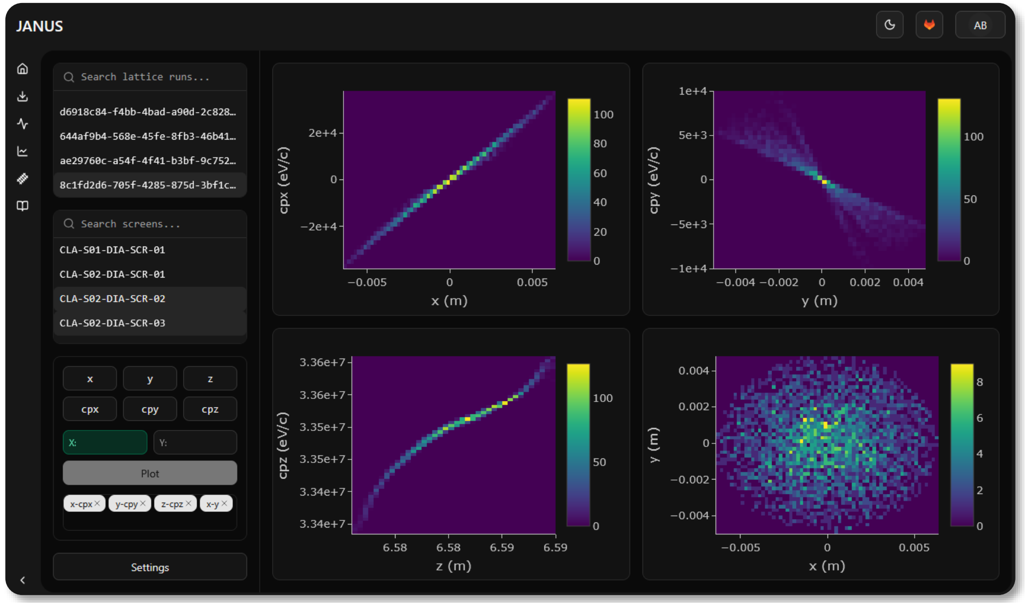
Above: Video showing the 250 MeV/c CLARA beam in a spectrometer line. The beam recovers from an RF trip within a few seconds.

> *"The* ***stability*** *and beam quality at CLARA is… comparable to other state-of-the-art facilities"*
>
> *"The robust and* ***stable beam*** *allowed for rapid irradiation [of samples]"*
>
> *"The working point provided excellent* ***stability*** *compared to similar facilities"*
>
> **– Anonymised User Feedback**

Software and Machine Learning

M. King *et al.*, arXiv:2509.19794 (2025)
A.D. Brynes *et al.*, arXiv:2604.19101 (2026)
J. Jones *et al.*, in Proc. IPAC26, **WEV6003** (2026)

- Most high-level CLARA software is based on CATAP, a python-based **middle layer** that simplifies interactions with the accelerator **hardware**
- A simulation-based **digital twin** has recently been deployed on CLARA, for **online modelling** of the accelerator and setup optimization
- CLARA is an ideal test facility for **machine learning** (ML) and artificial intelligence (AI). Many applications are in development:
  - ✓ Photoinjector laser pulse shaping
  - ✓ Magnet hysteresis modelling,
  - ✓ Reinforcement learning,
  - ✓ Virtual diagnostics,
  - ✓ Agentic control,



Above: Web interface for the simulation-based CLARA digital twin

Closing the Loop: Deploying Auto-Generating Digital Twins for Particle Accelerators

A. D. Brynes,[1,2,*] M. King,[1,2,†] K. R. L. Baker,[3] R. Banerjee,[3] R. Clarke,[4] D. J. Dunning,[1,2] J. K. Jones,[1,2] M. Leputa,[3] A. E. Pollard,[1,2] M. Romanovschi,[3] M. Shaw,[4] and N. Ziyan[1,2]
[1] *Accelerator Science & Technology Centre, STFC Daresbury Laboratory, Warrington, United Kingdom*
[2] *Cockcroft Institute, Warrington, United Kingdom*
[3] *ISIS Neutron and Muon Source, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, United Kingdom*
[4] *Technology Department, STFC Daresbury Laboratory, Warrington, United Kingdom*
(Dated: April 22, 2026)

The simulation of a physical system in a virtual replica, known as a digital twin, is a useful way to interrogate the system non-invasively, providing the ability to perform predictive maintenance and surveillance, and to investigate potential novel configurations without perturbing the system.

User Science Themes

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Advanced Diagnostics

Examples:
- Optical Transition Radiation (OTR),
- Coherent Transition Radiation (CTR)

Medical Applications

Examples:
- FLASH dosimetry,
- VHEE beam delivery,
- Radiobiology studies

Compact Accelerators

Examples:
- Beam driven plasma acceleration,
- Active plasma lenses

AI for Accelerators

Examples:
- Virtual diagnostics,
- Reinforcement learning optimisation

Laser Based Accelerators

Examples:
- Laser-plasma acceleration,
- Inverse Compton scattering

First Friendly User Run (Q1 2026)

Planned Friendly User Run (Q2 2026)

After FEBE Laser Commissioning (Q3 2026)

Comparison with European Facilities

Science and Technology Facilities Council

D. Angal-Kalinin *et al.*, in Proc. IPAC23, **MOZG1** (2023)

Updated from IPAC23 talk:
"Electron Beam Test Facilities for Novel Applications"

	CLARA	ARES	CLEAR	FLUTE	PITZ	SPARC Lab
	UKRI	DESY.	CERN	KIT Karlsruher Institut für Technologie	DESY.	INFN
Accelerator Components R&D	✓	✓	✓	✓	✓	✓
Beam Diagnostics R&D	✓	✓	✓	✓	✓	✓
Novel Acceleration (DWA, DLA)	✓	✓				
Novel Acceleration Using High Power Lasers (PWFA, LWFA*, THz)	✓					✓
Radiation Sources				✓	✓	✓
Plasma Lens Development	✓		✓			
VHEE FLASH Radiotherapy	✓		✓			
Other Medical Applications		✓		✓		
Irradiation Experiments†			✓			

** External injection into laser wakefield acceleration (LWFA)*
† Excluding radiotherapy applications

Friendly User Programme

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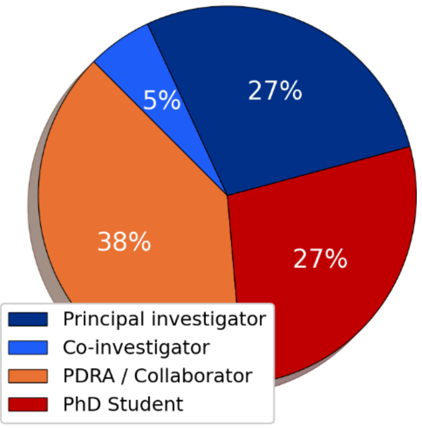
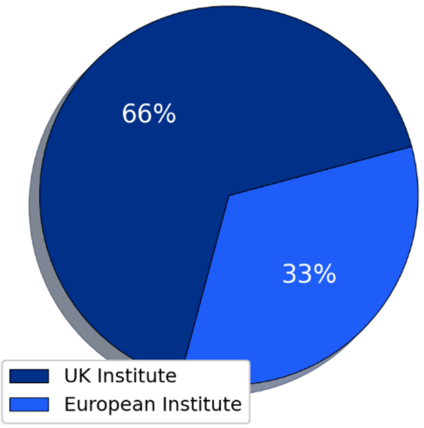
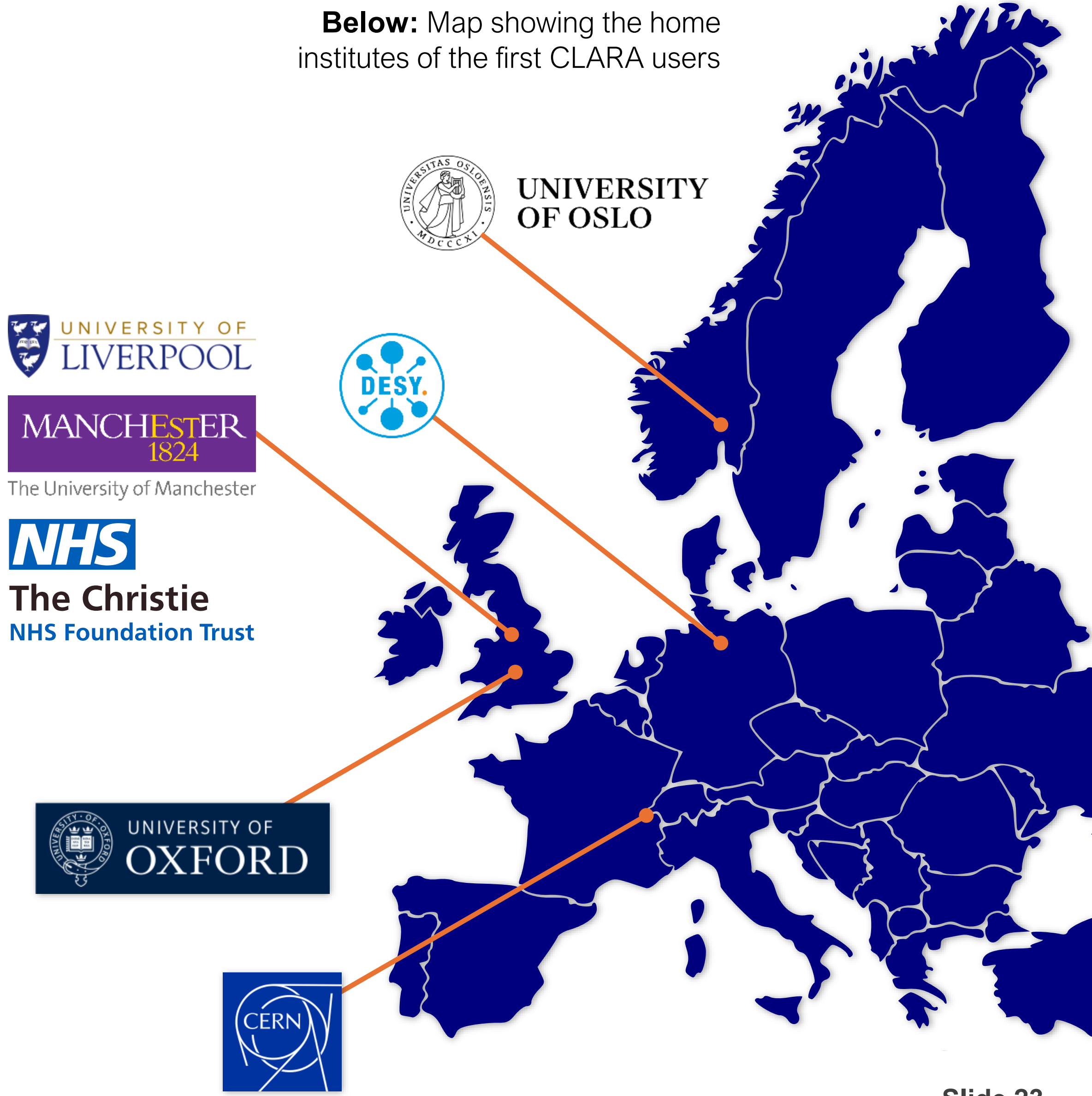
- The first CLARA **user experiments** took place between January – April 2026

- Experiments were specifically **selected** to:
  - ✓ Deliver high-impact science,
  - ✓ Cover a wide range of science themes,
  - ✓ Build on successful experiments at other facilities,
  - ✓ Exploit the full capabilities of the CLARA accelerator,
  - ✓ Complement ongoing commissioning work





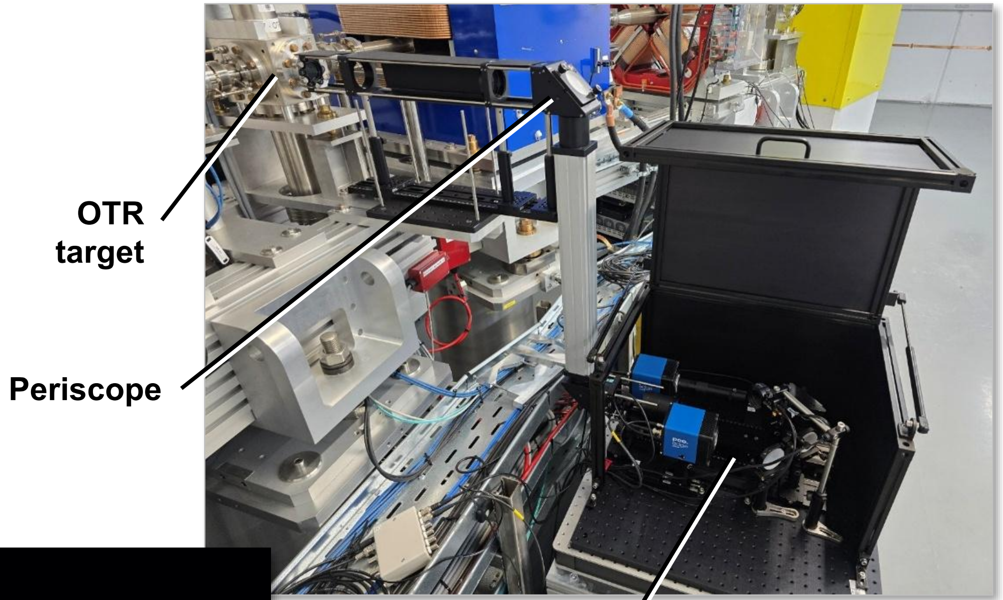
Below: Map showing the home institutes of the first CLARA users



Optical Transition Radiation (OTR)

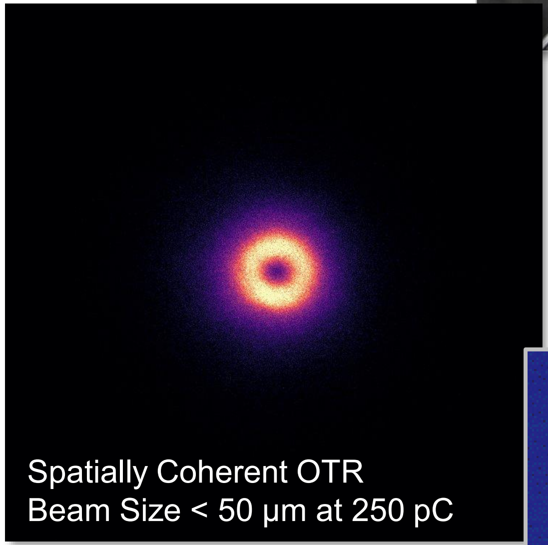
Lead Investigator: J. Wolfenden (Liverpool University)

- Experiment involved measurements of the transverse beam optics, using an **OTR target** located after the FEBE hutch
- Aimed to characterize the resolution of **single-shot emittance measurements**, made via an optical pepper pot technique
- The FEBE beamline was used to:
  - ✓ **Benchmark** OTR measurements against quadrupole scans,
  - ✓ Deliver specific **Twiss parameters** to the OTR target

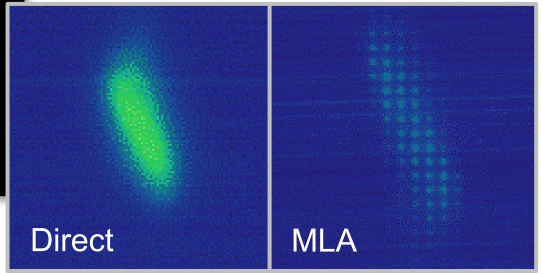


Light box with optical paths for:

- Direct imaging of OTR light
- OTR imaging via a multi-lens array (MLA)



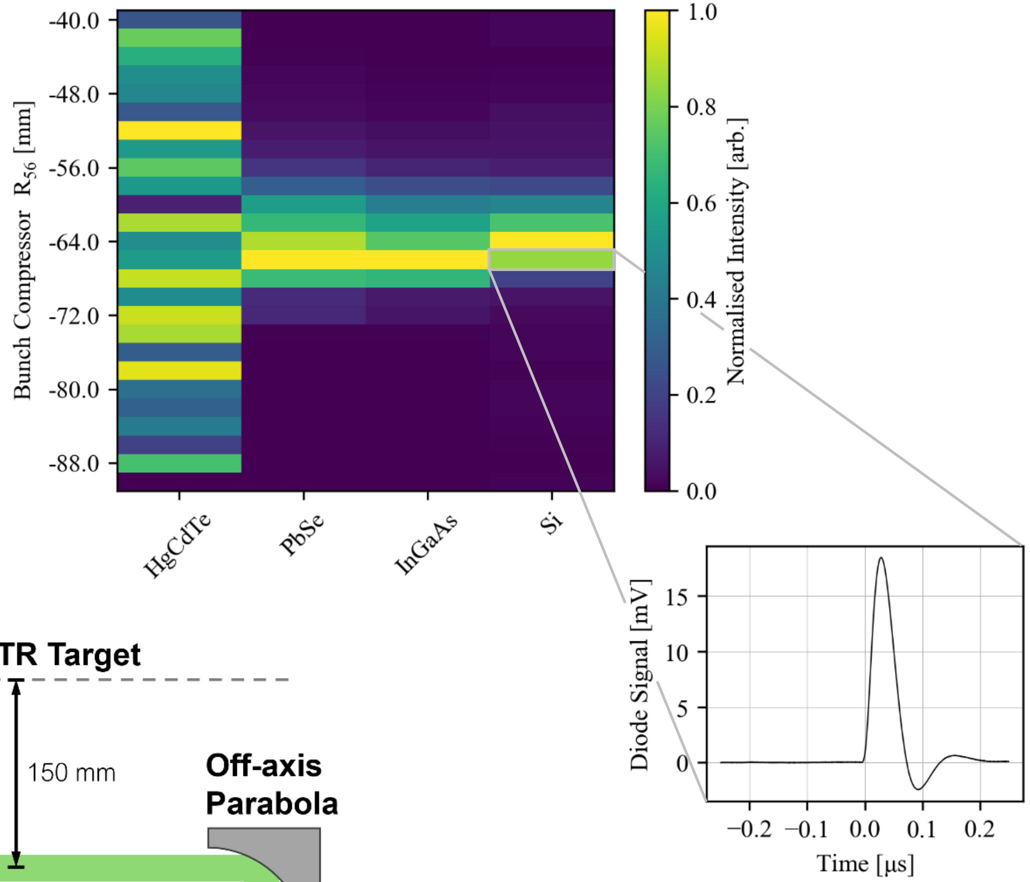
Spatially Coherent OTR
Beam Size < 50 μm at 250 pC

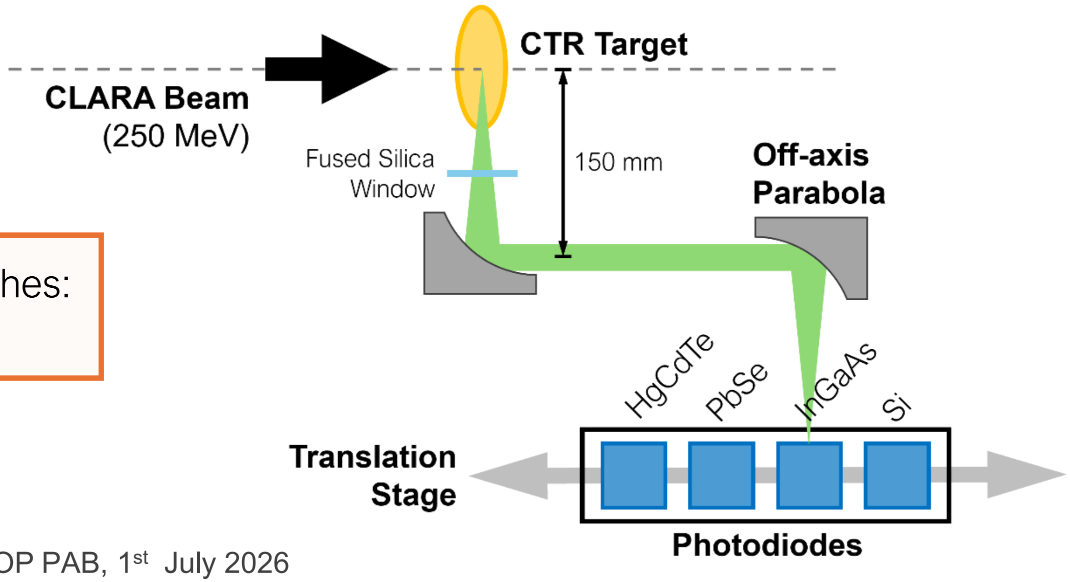


Coherent Transition Radiation (CTR)

Lead Investigator: W. Kuropka (DESY ARES)

- Experiment aimed to demonstrate a CTR-based compression diagnostic for **ultra-short** (< 10 fs), **low charge** (< 5 pC) beams
- Signals were measured with several **photodiodes**, mounted next to a CTR target just before the FEBE hutch
- Minimized the **bunch length** by adjusting the VBC R_{56} to maximize the CTR signal at short wavelengths





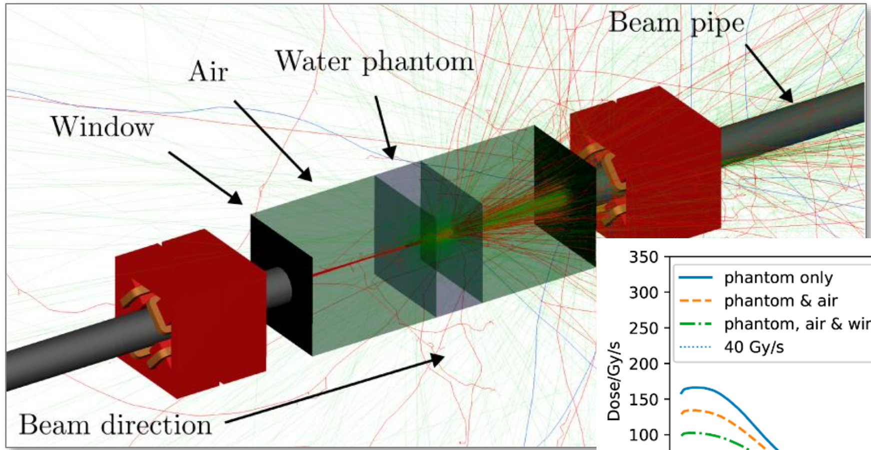
Delivered **ultra-short** electron bunches:
≲5 fs duration at ~3.5 pC

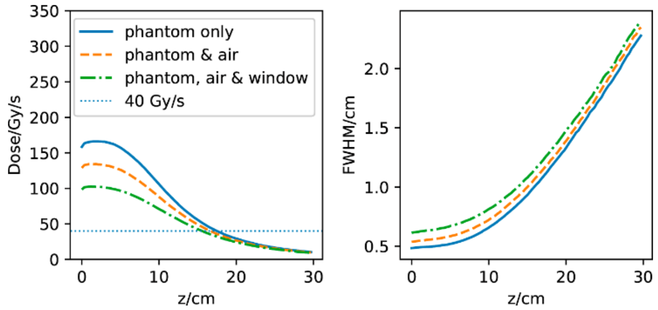
Medical Applications

D. Angal-Kalinin *et al.*, Front. Phys. **12**, 1496850 (2024)

- CLARA is a valuable test facility for new radiotherapy methods using **very high energy electrons** (VHEE)
- Simulation studies have indicated that CLARA can deliver **FLASH dose rates** (> 40 Gy/s) to the FEBE user area
- FLASH dose rates are of interest due to evidence that they deliver similar tumour control while **sparing healthy tissue**
- The VHEE'25 workshop was held at Daresbury in Sept. 2025

See Roger Jones' talk about
VHEE radiotherapy
after the coffee break





Left: Visualisation of Monte Carlo dose rate calculations with the 250 MeV CLARA beam

Above: Participants of the VHEE'25 workshop

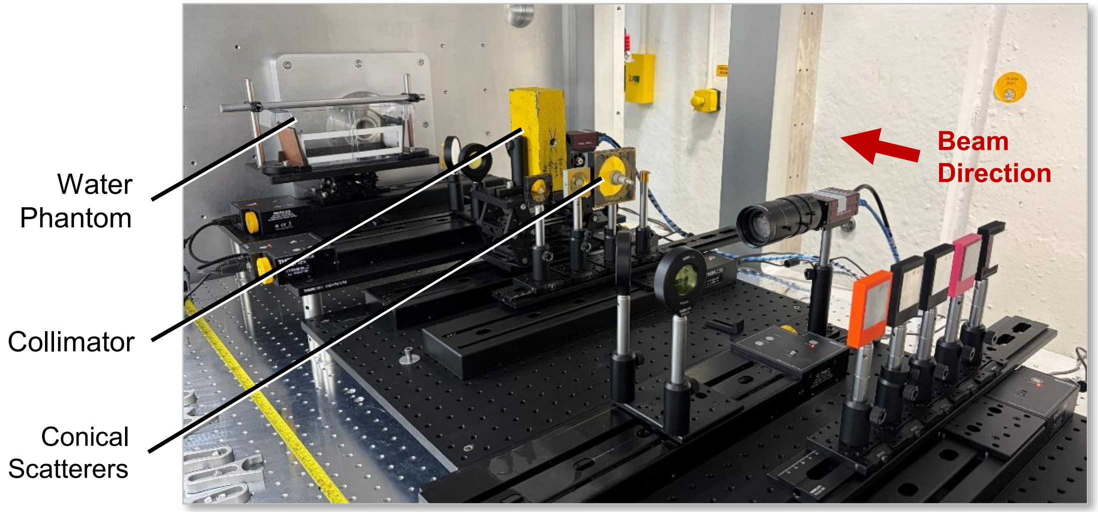
VHEE Scatterers

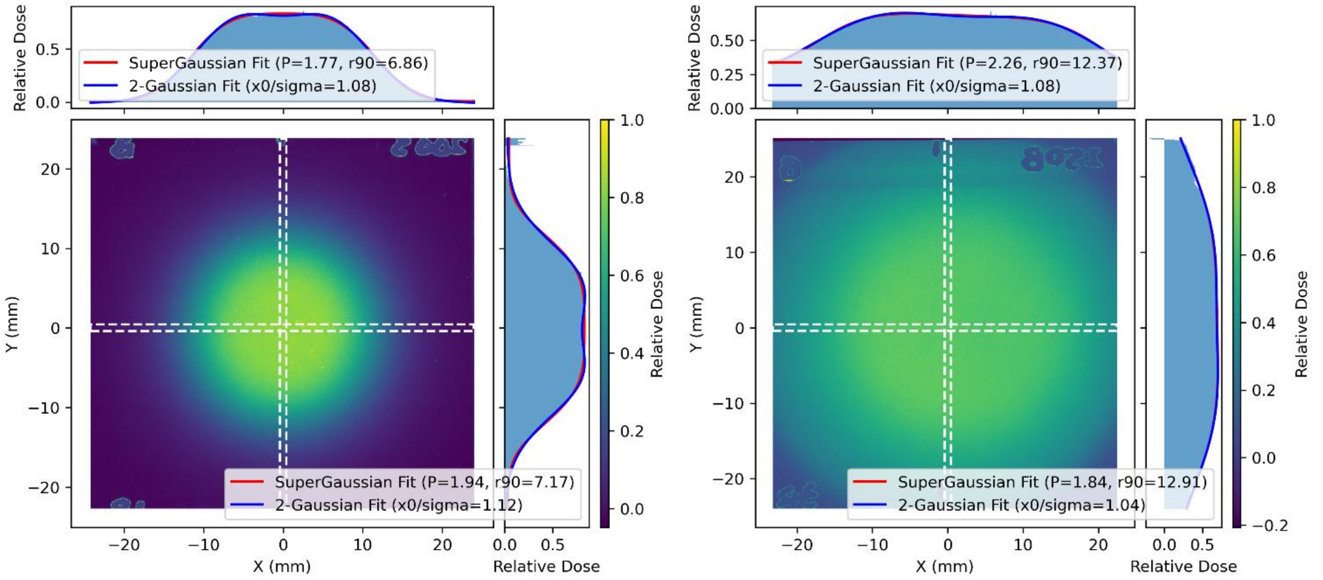
C. Robertson *et al.*
NIM A **1082**, 170943 (2026)

Science and Technology Facilities Council

Lead Investigator: M. Dosanjh (Oxford University and CERN)

- The first **in-air experiment** carried out in either of the FEBE experimental chambers
- Aimed to generate large (~1 cm), **uniform beam profiles** suitable for Very High Energy Electron (VHEE) radiotherapy
- Successfully produced uniform beams at energies up to 250 MeV, using various **scatterer configurations**
- Builds on previous work with 200 MeV beam at CLEAR (CERN)





Top Right: Photo of the experimental setup inside the second FEBE chamber

Bottom Right: Analysis of RCF films showing uniform electron beam profiles

VHEE Cell Irradiation

K.L. Small *et al.*, Sci. Rep **11**, 3341 (2021)
D. Angal-Kalinin *et al.*, Front. Phys. **12** 1496850 (2024)
K. Small *et al.*, NIM B **565**, 165752 (2025)

Science and Technology Facilities Council

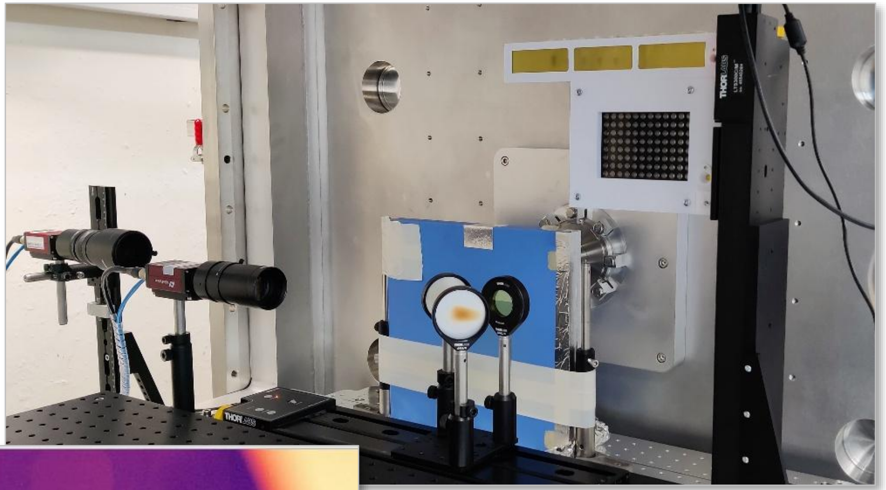
Lead Investigator: R.M. Jones (Manchester University)

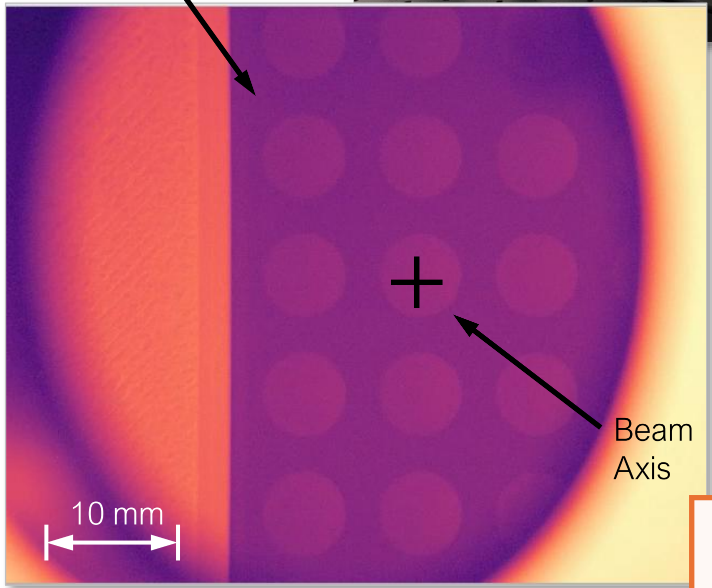
- Dosimetry studies to establish the electron beam parameters required to achieve **FLASH dose rates** (> 100 Gy/s) at CLARA

European first: VHEE FLASH irradiation of **cancer cells** (A549 lung adenocarcinoma) with the 250 MeV electron beam

- Experiment will study **cell survival** and **DNA damage** after VHEE irradiation at conventional and FLASH dose rates

- Builds on **previous studies** at CLARA, ARES (DESY) and CLEAR (CERN)





Above: Photo of the experimental setup inside the FEBE chamber

Left: Video showing delivery of the CLARA electron beam to samples held in a 96-well cell plate

See talk by **Kristina Small** at 11:20 today

MANCHESTER 1824
The University of Manchester

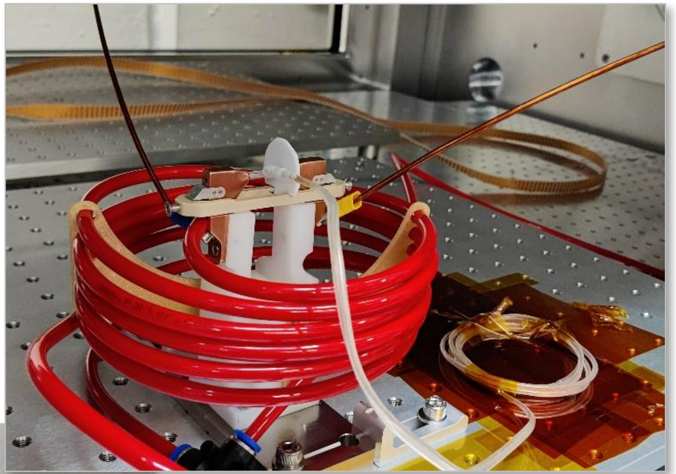
NHS
The Christie
NHS Foundation Trust

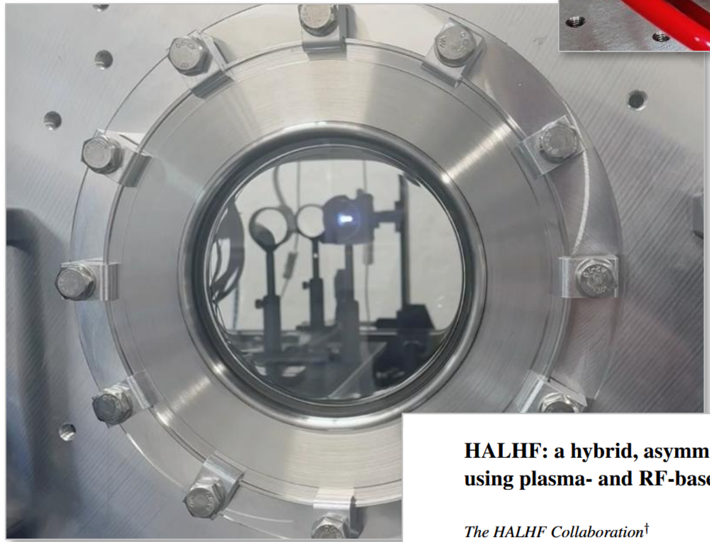
Plasma Acceleration - Goals

Lead Investigator: R. D'Arcy (Oxford University)

- The HALHF Collaboration plan to explore concepts for **novel accelerator staging** (for high energy) and **repetition rates** (for high luminosity) at CLARA
  - ✓ Plan benefits from unique, flexible, modular infrastructure
  - ✓ To be carried out in a multi-year phased approach

- **Experimental goals** (this beam time):
  - ✓ Prove plasma-accelerator infrastructure at CLARA, and generate plasma with a discharge capillary
  - ✓ Drive a plasma wake with the CLARA beam
    Goal: Generate GV/m (decelerating) fields
  - ✓ Focus CLARA beams with an active plasma lens
    Goal: Generate >100 T/m (focussing) fields





Above: Plasma cell in the FEBE experimental chamber

Left: First (argon) plasma generation

arXiv:2503.19880

HALHF: a hybrid, asymmetric, linear Higgs factory using plasma- and RF-based acceleration

The HALHF Collaboration†

1 Scientific context

The previous EPPSU concluded that the next major particle-physics facility should be an e^+e^- Higgs Factory; it also prioritised R&D in accelerator science [1]. Plasma-based acceleration is an emerging accelerator technology that has shown tremendous progress over the past decade, to the extent that, for the first time, beam-driven plasma-wakefield acceleration (PWFA) approaches some of the parameters required to produce a viable high-energy e^+e^- collider for particle physics [2–5].

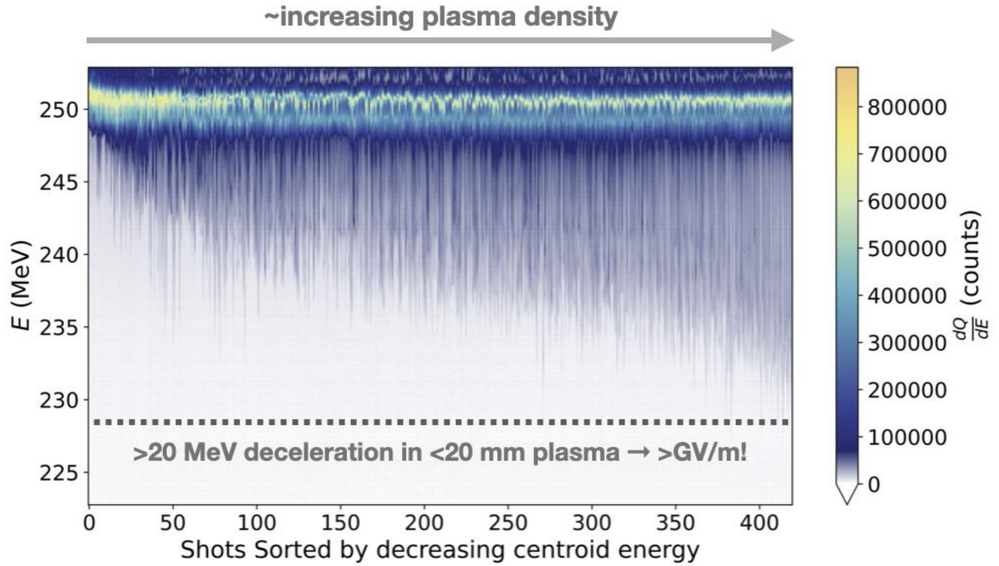
Plasma Acceleration - Results

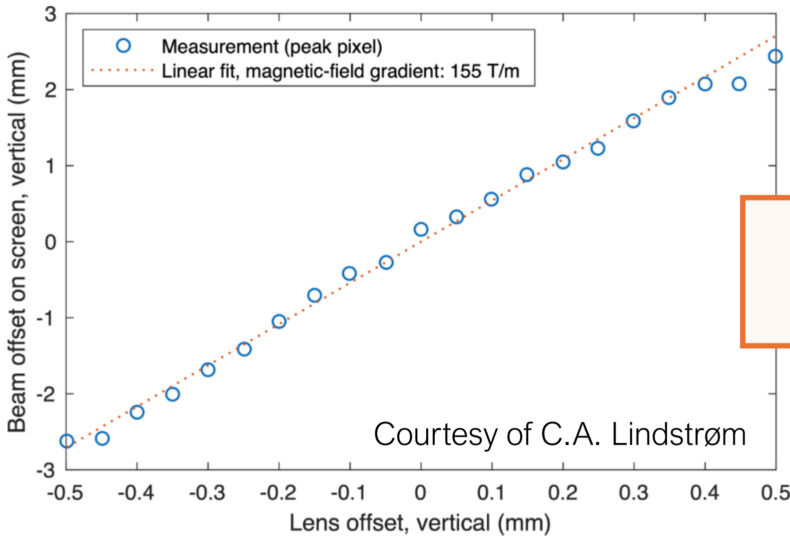
Lead Investigator: R. D'Arcy (Oxford University)

- **All goals achieved!**
  - ✓ ~GV/m electric fields
  - ✓ ~150 T/m magnetic fields

Milestone: First beam-driven plasma "accelerator" in the UK, and the first active plasma lensing at CLARA

- **Next steps** (in subsequent beam times)
  - ✓ Novel interstage optics scheme (for **staging** of plasma-accelerated beams)
  - ✓ Plasma acceleration of **bunch trains** with HALHF properties (~10 ns separation, 100 Hz)
  - ✓ Energy-mapping studies and high average power **plasma sources**





See talk by **Meg Savage** Tuesday at 11:15

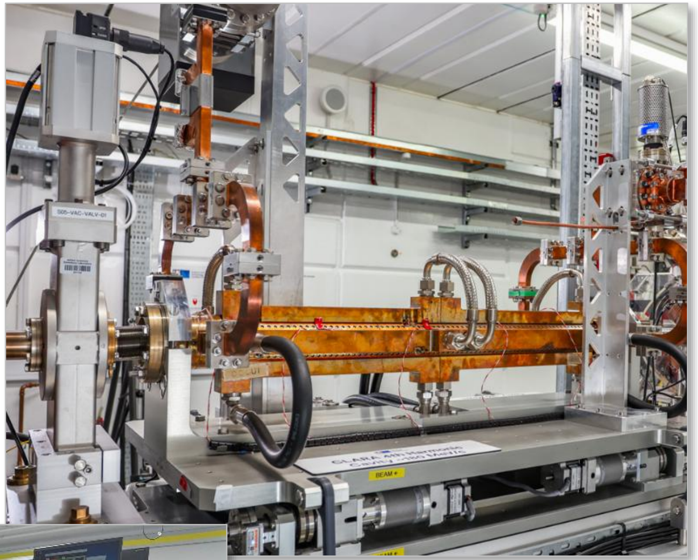
Future Plans

CLARA is delivering high-brightness electron beams to **high-impact user experiments**

More milestones are expected over the coming months…

- ✓ Commissioning of the **fourth harmonic cavity**,
- ✓ **120 TW laser** transport into the FEBE hutch,
- ✓ First experiments combining the CLARA electron beam and FEBE laser

Further **user experiments**, involving machine learning and the FEBE laser, are planned for **later this year**



Above: Fourth harmonic cavity installed on the CLARA beamline

Left: 120 TW laser installed in a room above the FEBE hutch

Science and Technology Facilities Council

Thank You for Listening!

Questions are Very Welcome

CLARA at IPAC26

www.ipac26.org/prepress

TUP3075	In-situ cathode measurements (*A. Pollard*)
TUP3076	Dark current measurements (*F. Jackson*)
WEV6003	High-level software (*J. Jones*)
WEP6091	Dechirper commissioning (*T. Overton*)
WEP6092	Phase space tomography (*M. Johnson*)
WEP6104	High-level RF interfaces (*N. Joshi*)
WEP6171	Automated RF conditioning (*M. King*)
THP2100	Compression and linearisation (*J. Jones*)
THP2143	Cs_2Te cathode production (*H. Churn*)
THP2144	High-power RF conditioning (*A. Gilfellon*)