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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

IPAC26

The Cockcroft Institute
of Accelerator Science and Technology

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

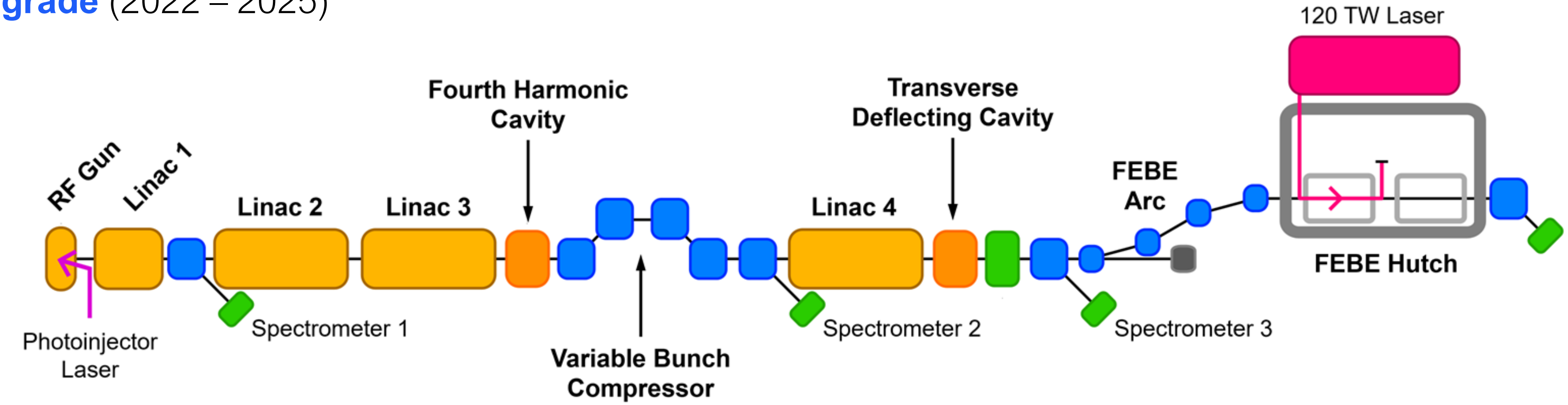
Introduction

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)

- 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)

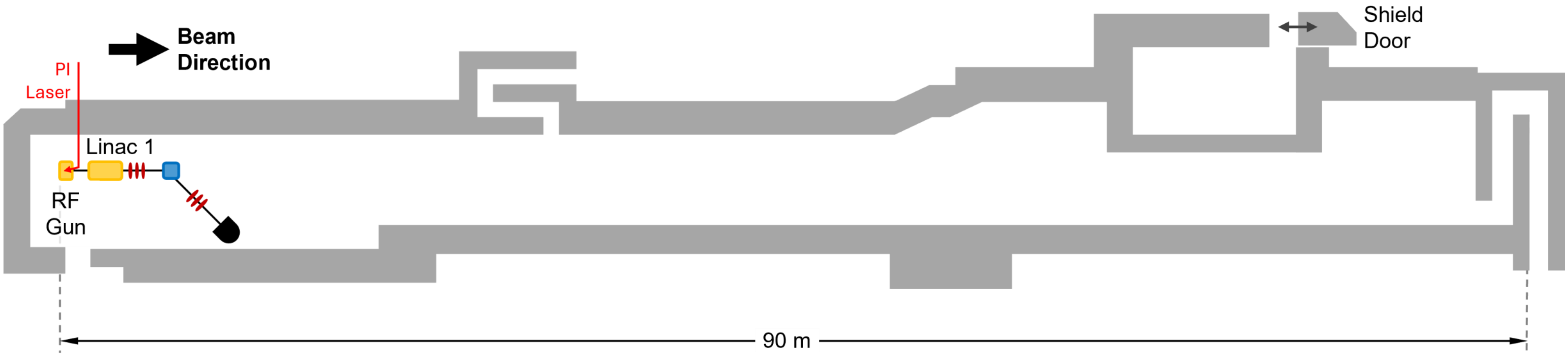
Parameter	Low Charge	High Charge
Repetition Rate [Hz]	1 - 100	
Bunch charge [pC]	5	250
Bunch length [fs]	50	100
Energy spread [%]	< 1	< 5
Spot Size at IP [μm]	20	100
Norm. Emittance [μm]	2.0	5.0

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



CLARA Front End Layout

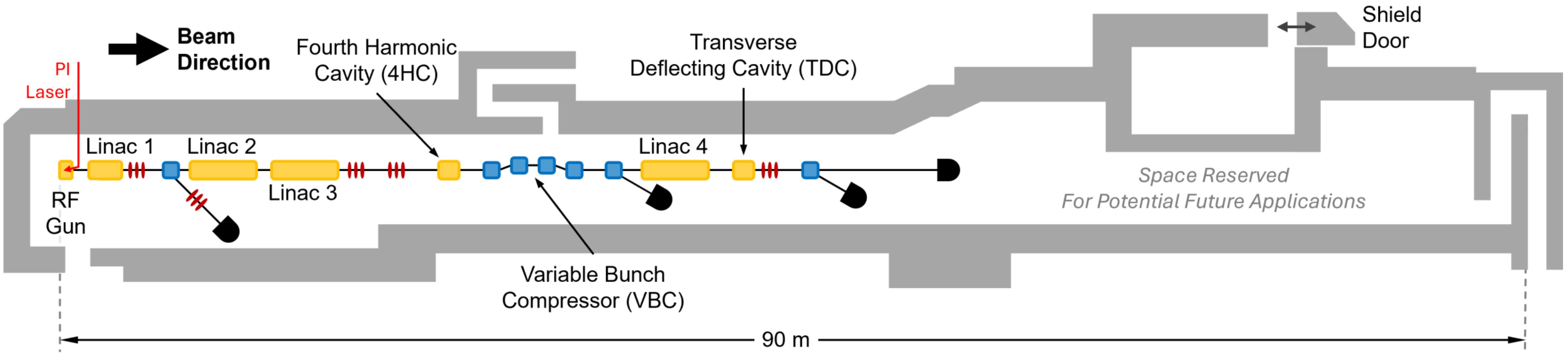
D. Angal-Kalinin *et al.*, PRAB **23**, 044801 (2020)



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

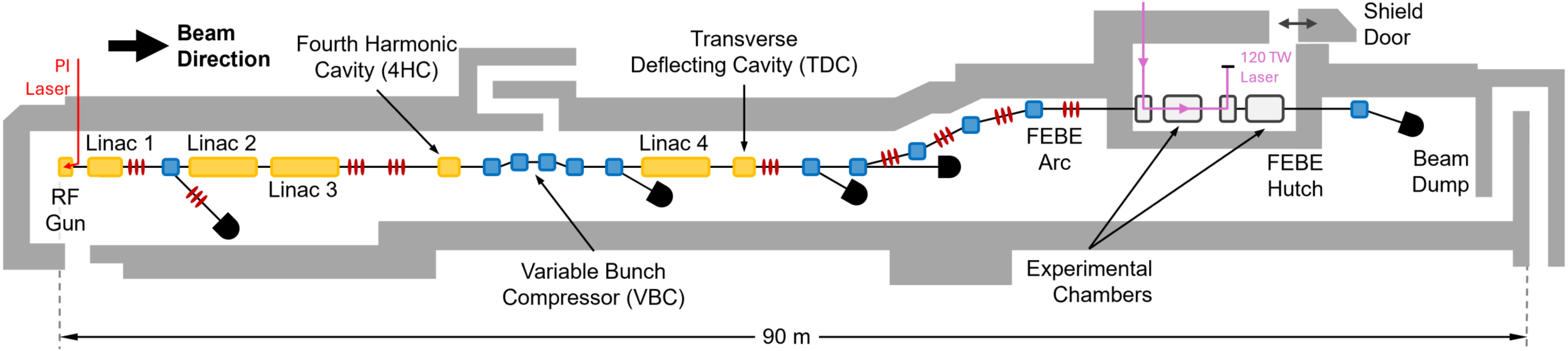
Example Technical System	**CLARA Front End (35 MeV)**
RF Structures	2
Magnets	22
Diagnostic Systems	13
Vacuum Gauges and Pumps	57

CLARA Layout



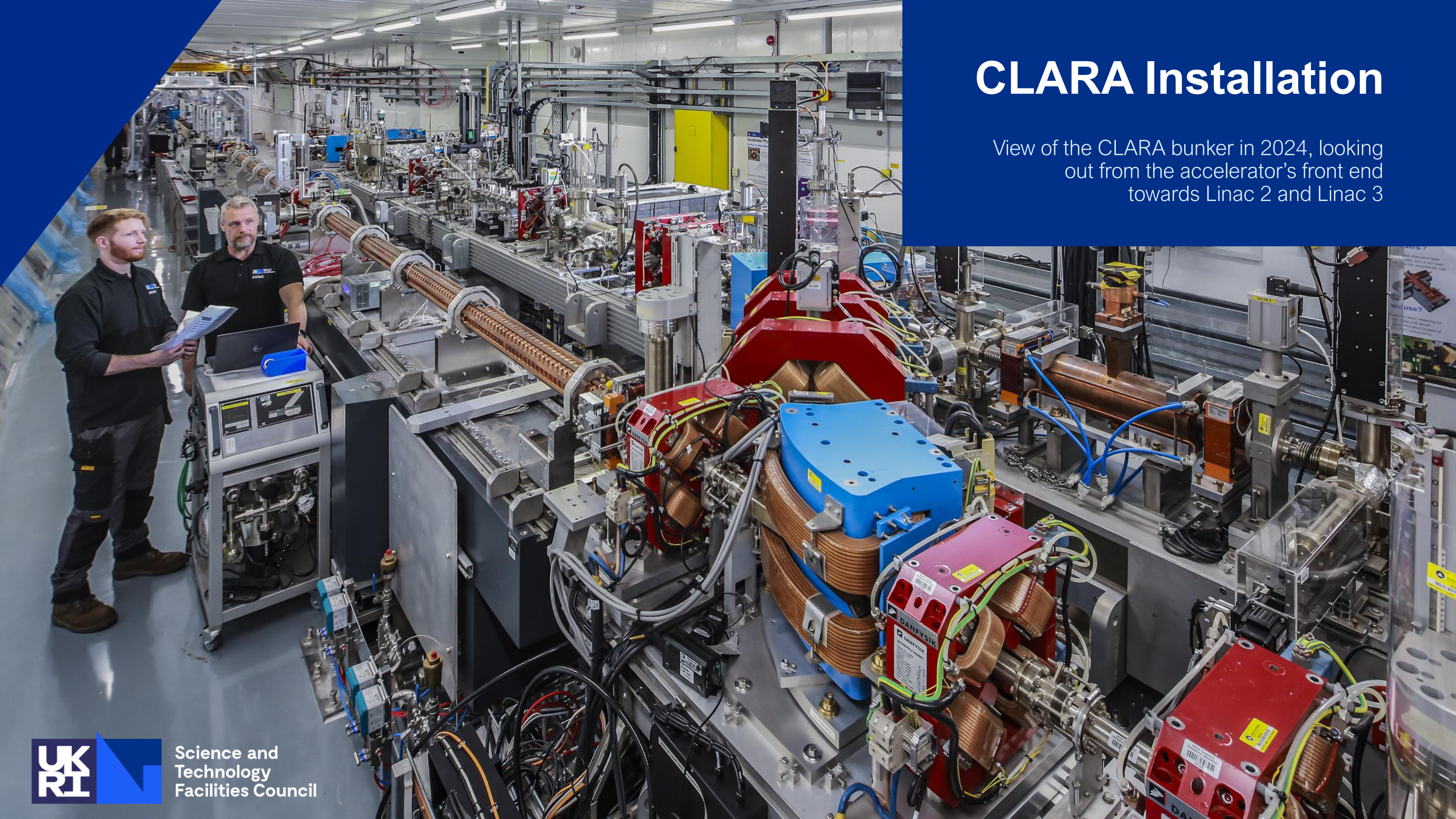
Example Technical System	**CLARA Front End (35 MeV)**	**CLARA (250 MeV)**
RF Structures	2	7
Magnets	22	77
Diagnostic Systems	13	65
Vacuum Gauges and Pumps	57	109

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

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FEBE User Area on CLARA

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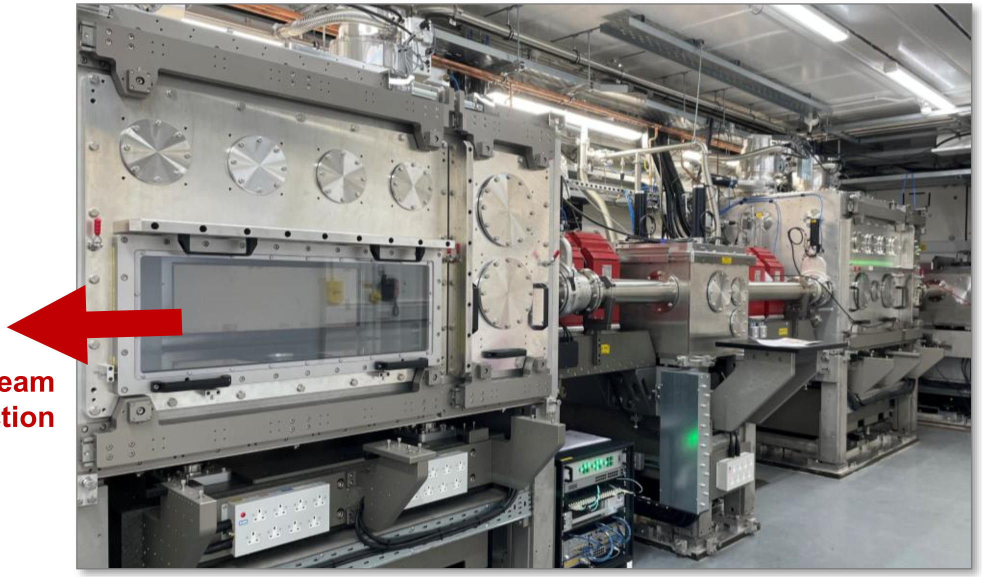
E.W. Snedden *et al.*, PRAB **27**, 041602 (2024)

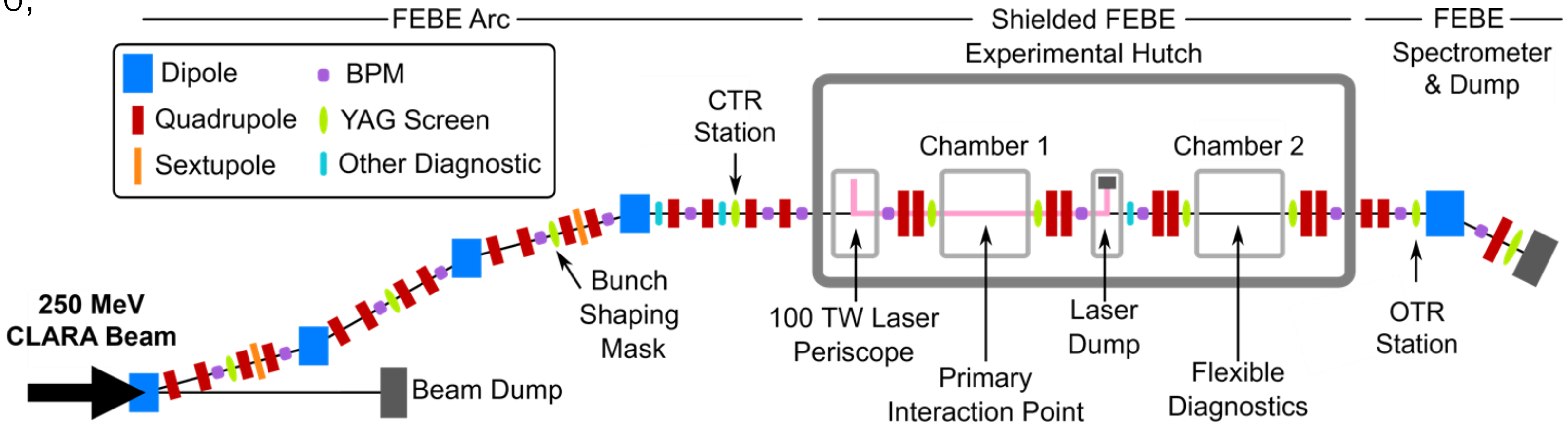
- The Full Energy Beam Exploitation (FEBE) beamline includes a dedicated user area in a **separately-shielded enclosure**

- 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



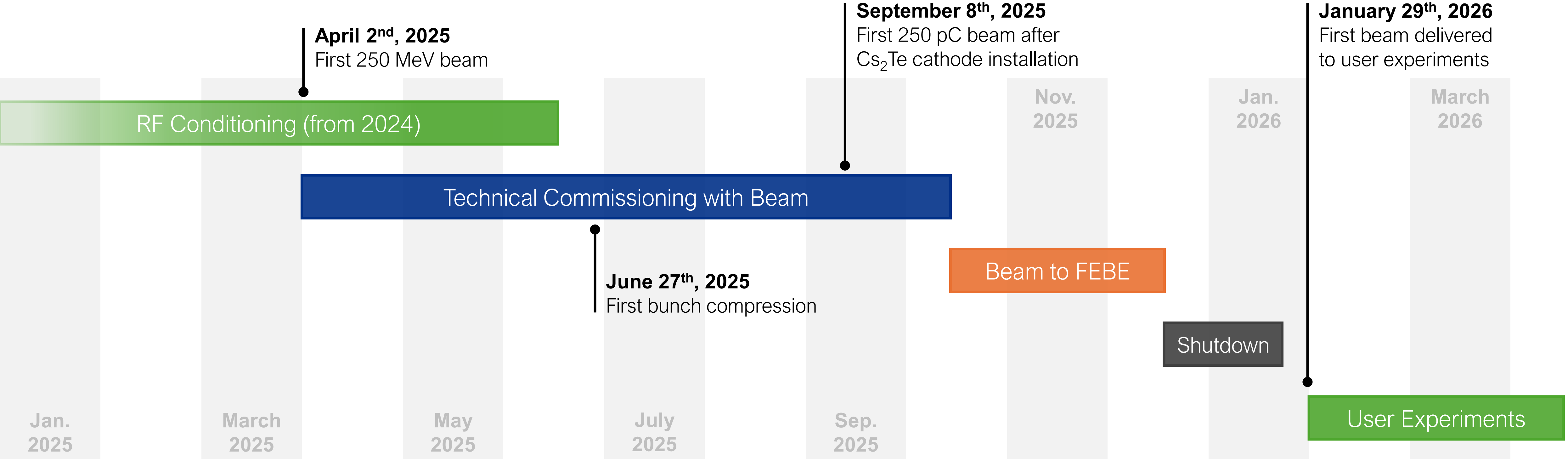
Beam Direction



Commissioning Timeline

- 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 planned for later this year, for detailed optimisation of the beam parameters

RF Conditioning
M. King (**WEP6171**)
A. Gilfellon (**THP2144**)



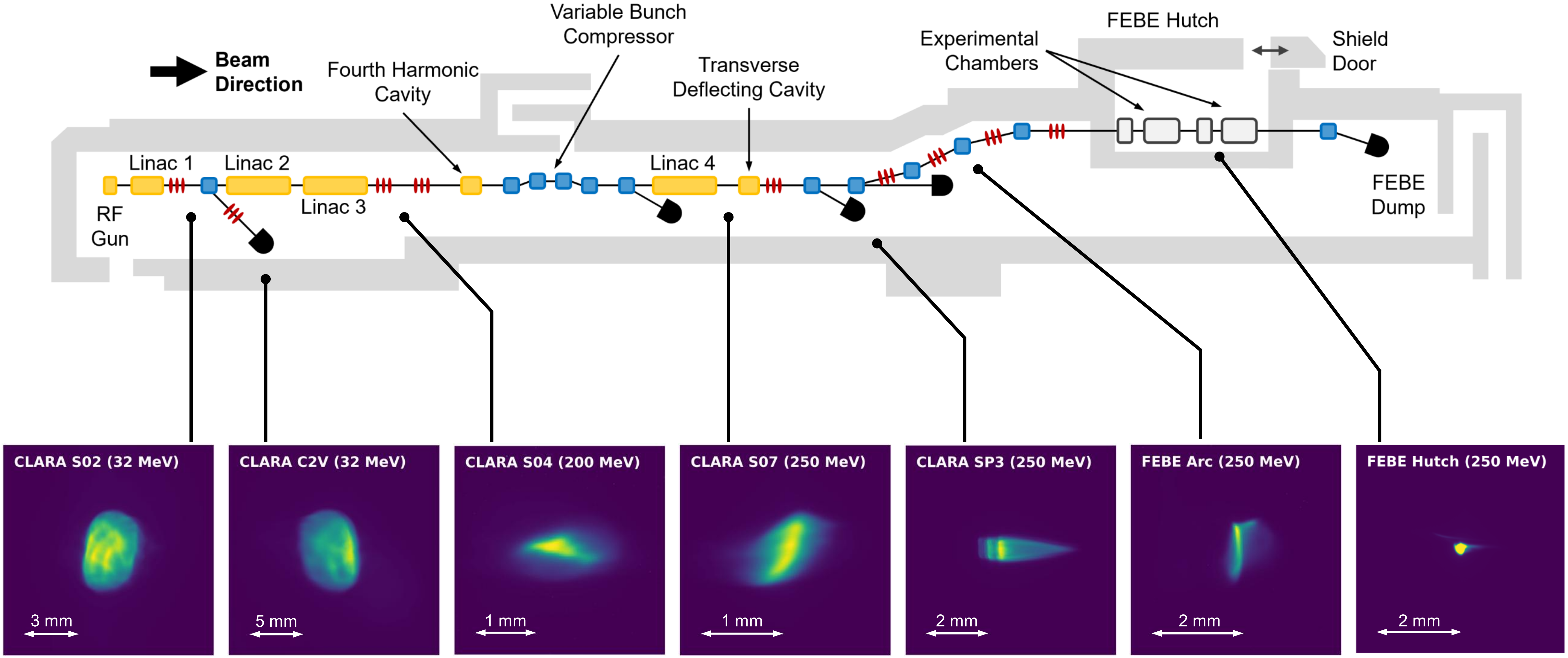
April 2nd, 2025
First 250 MeV beam

June 27th, 2025
First bunch compression

September 8th, 2025
First 250 pC beam after Cs_2Te cathode installation

January 29th, 2026
First beam delivered to user experiments

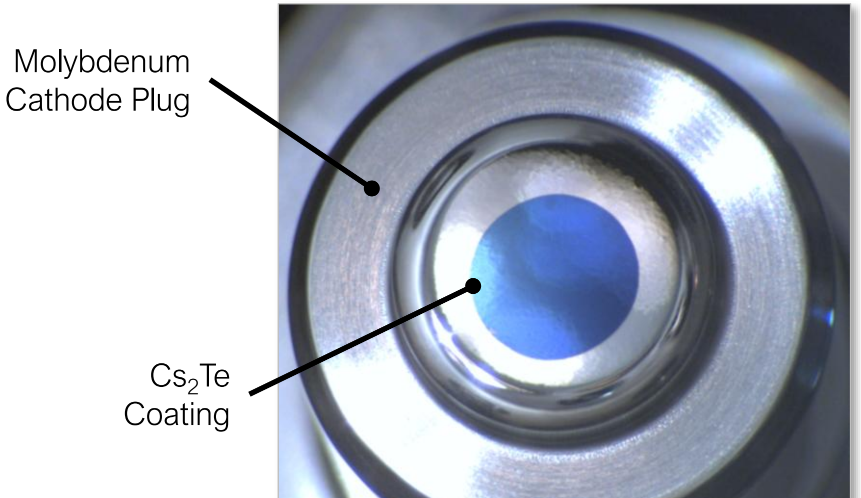
Beam Images (250 pC)

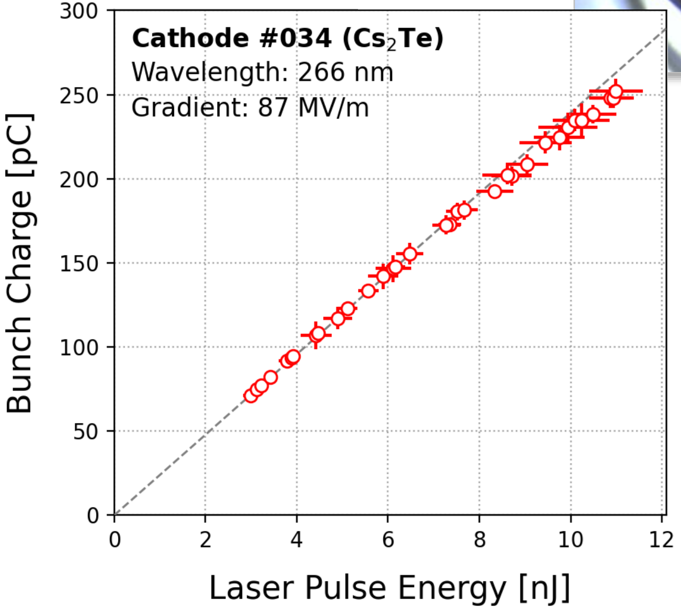


Cs_2Te Photocathodes

- 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 ~11% measured under operational conditions in the CLARA gun
- Laser energy now available for longitudinal **pulse shaping** in future

H. Churn (**THP2143**)
A. Pollard (**TUP3075**)
F. Jackson (**TUP3076**)





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

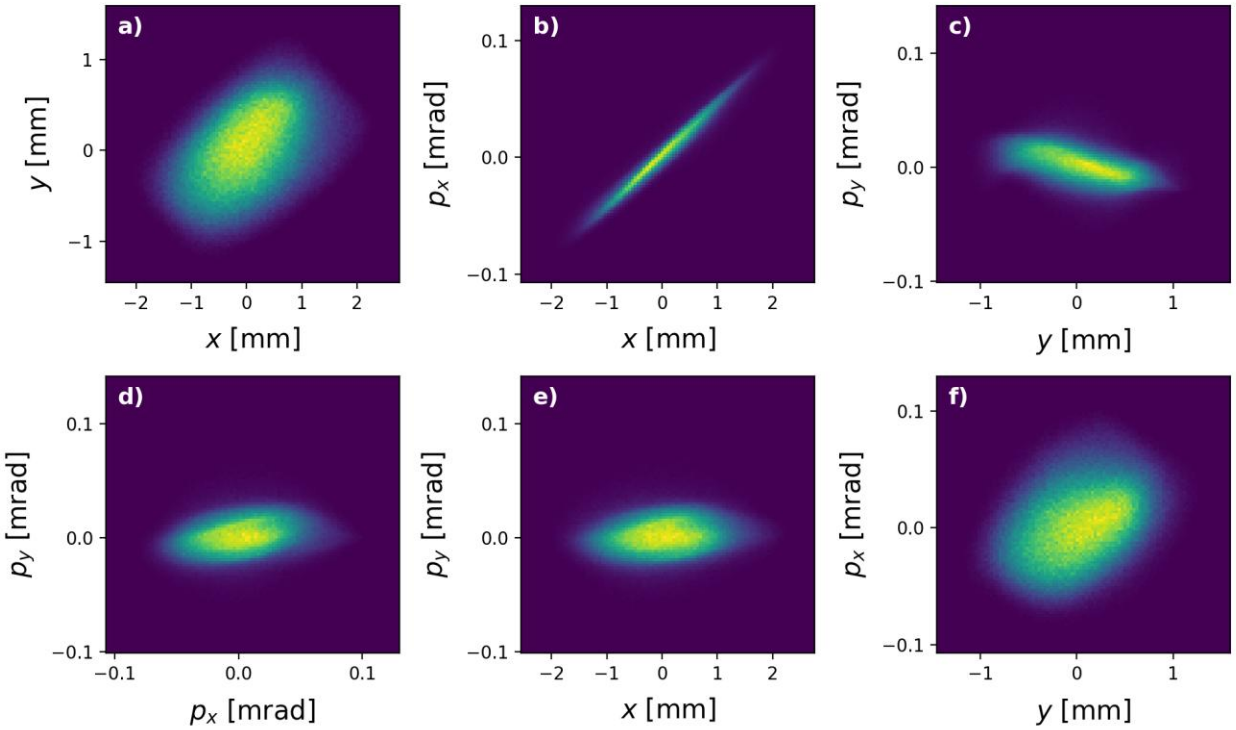
Left: Typical QE measurement for a CLARA photocathode

Emittance Measurements

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

- Emittance measurements are based on **quadrupole scans** throughout the CLARA beamline
- We 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

Beam Setup (250 pC)	**Horizontal Normalised Emittance [μm]**
Post-injector (35 MeV)	< 1.0
Uncompressed (250 MeV)	2.3
Compressed (250 MeV)	~5.0



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

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

M. Johnson (**WEP6092**)

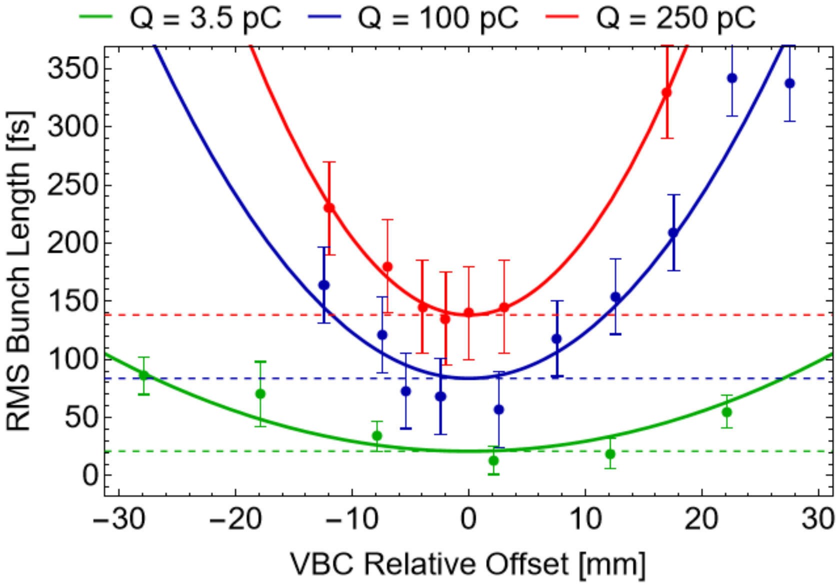
Longitudinal Dynamics

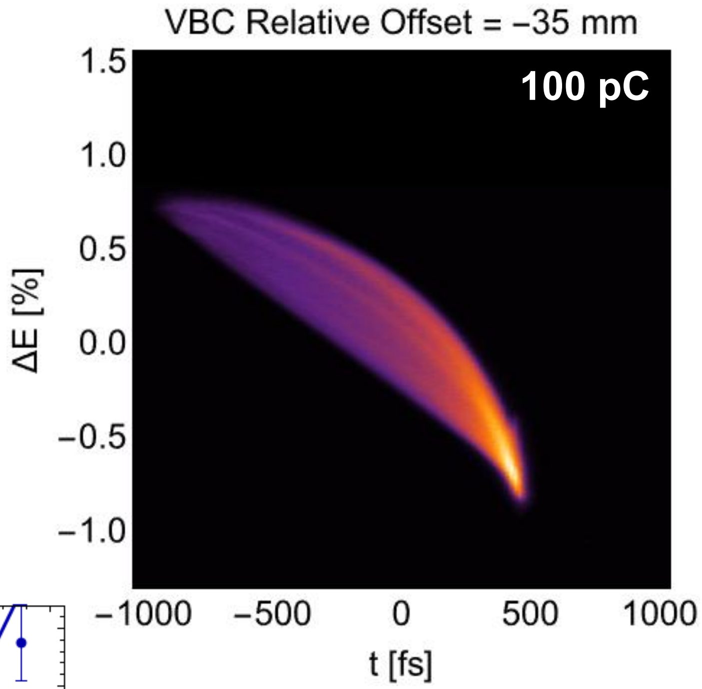
- The CLARA lattice allows **measurement and manipulation** of the beam's longitudinal phase space:
  - ✓ Variable bunch compressor (VBC)
  - ✓ Transverse deflecting cavity (TDC)
  - ✓ Passive dielectric dechirper

- 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

J. Jones (**THP2100**)
T. Overton (**WEP6091**)





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

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

User Science Themes

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)

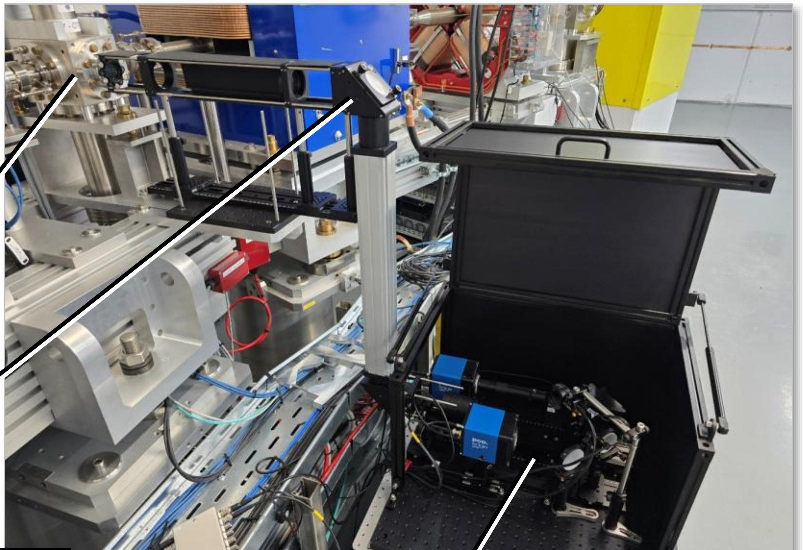
Planned Friendly User Run (Q2 2026)

After FEBE Laser Commissioning (Q3 2026)

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

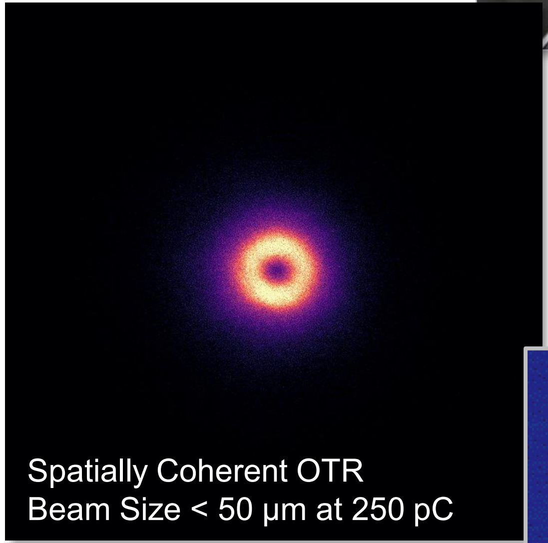


OTR target

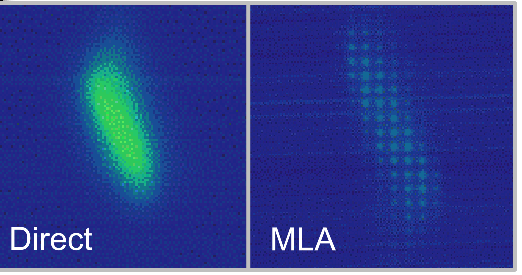
Periscope

Light box with optical paths for:

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



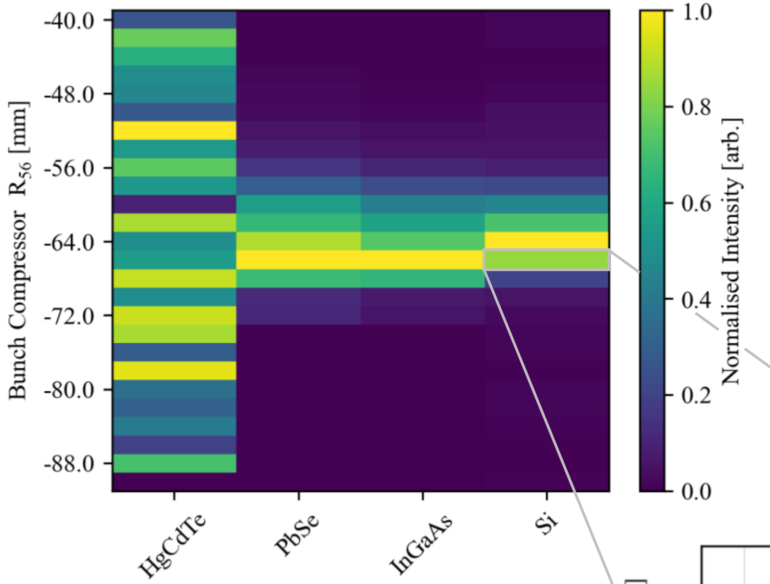
Spatially Coherent OTR
Beam Size < 50 µm at 250 pC

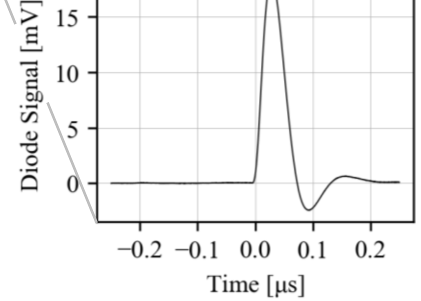


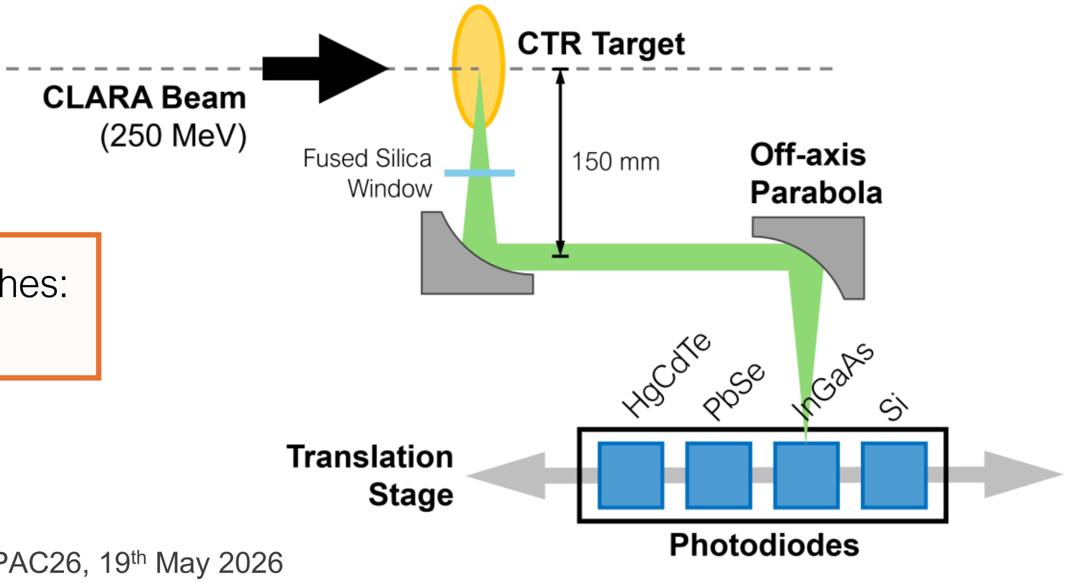
Coherent Transition Radiation (CTR)

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







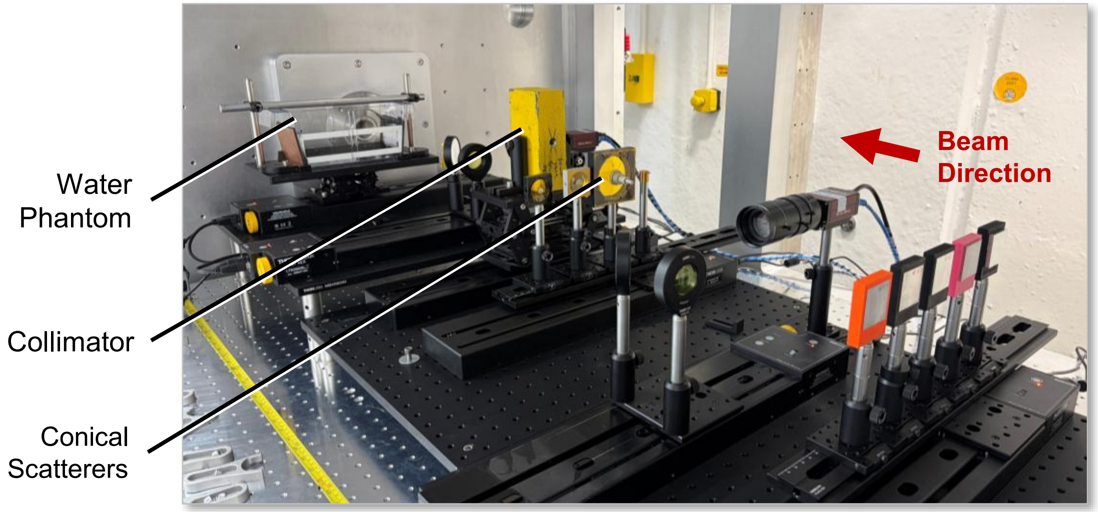
Delivered **ultra-short** electron bunches:
≲5 fs duration at ~3.5 pC

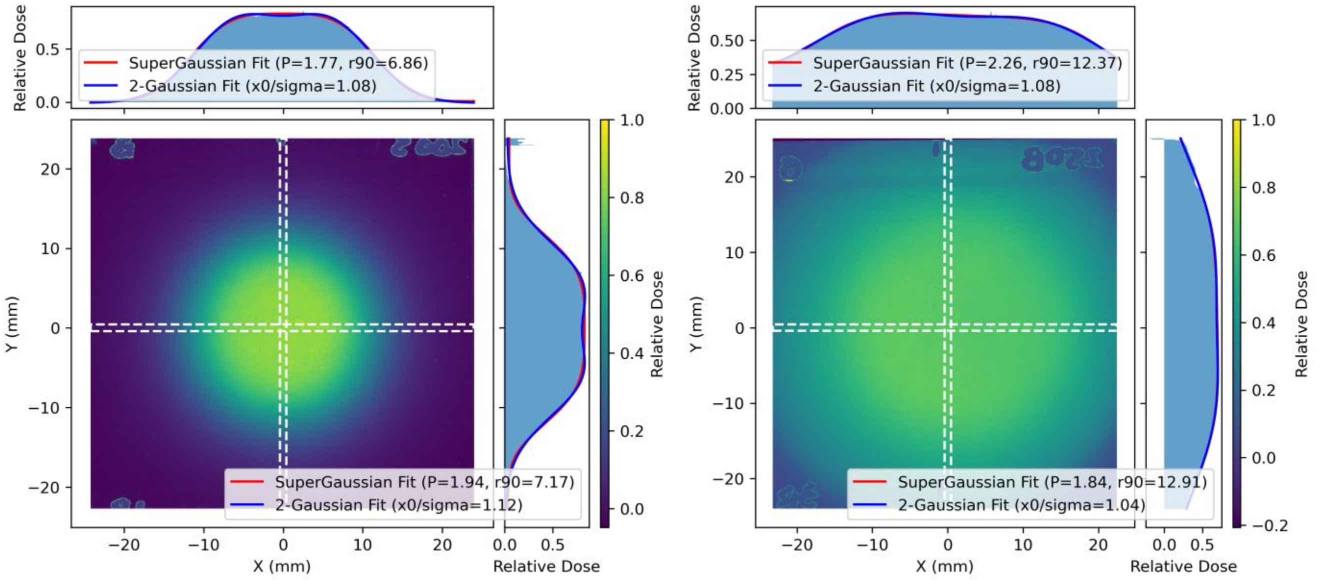
VHEE Scatterers

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

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)

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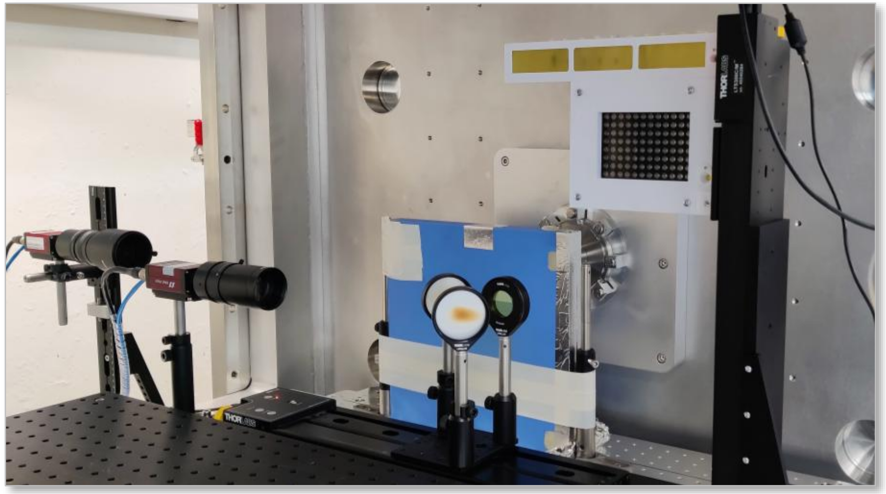
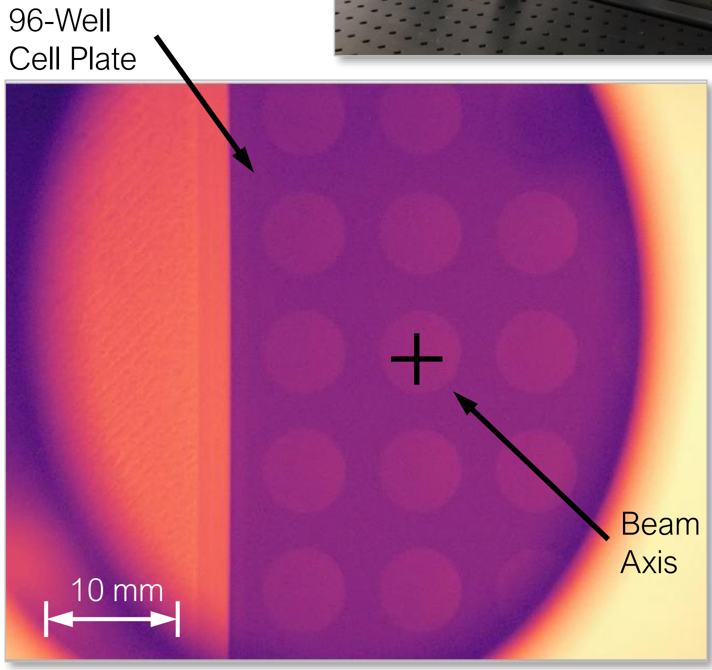
Lead Investigator: R.M. Jones (Manchester University)

- 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 **human 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

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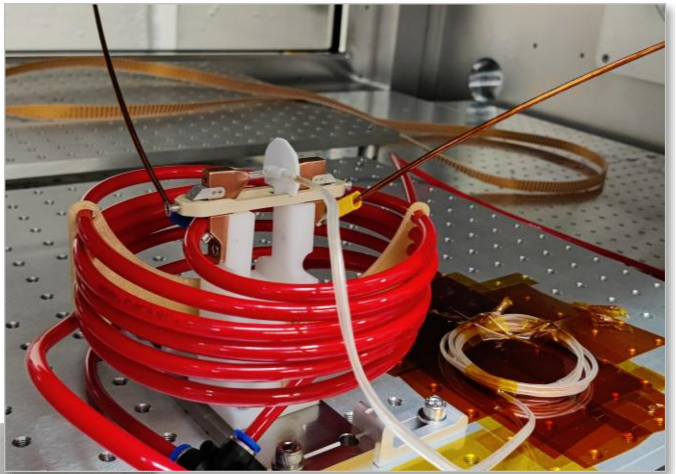
Plasma Acceleration - Goals

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

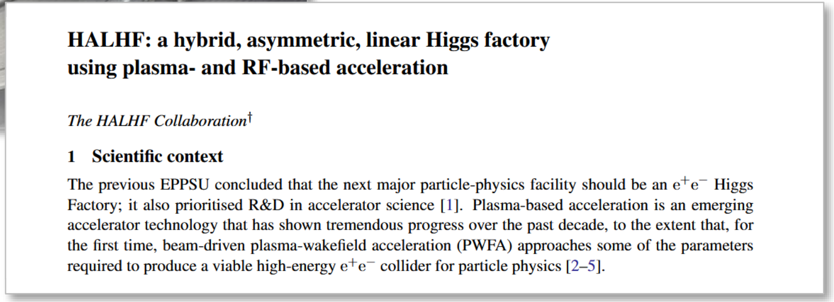
- **Experimental goals** (this beam time):
  - ✓ Prove plasma-accelerator infrastructure at CLARA, and generate plasma with a discharge capillary
  - ✓ Drive a plasma wake with the CLARA beam
Goal: Generate GV/m (decelerating) fields
  - ✓ Focus CLARA beams with an active plasma lens
Goal: Generate >100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

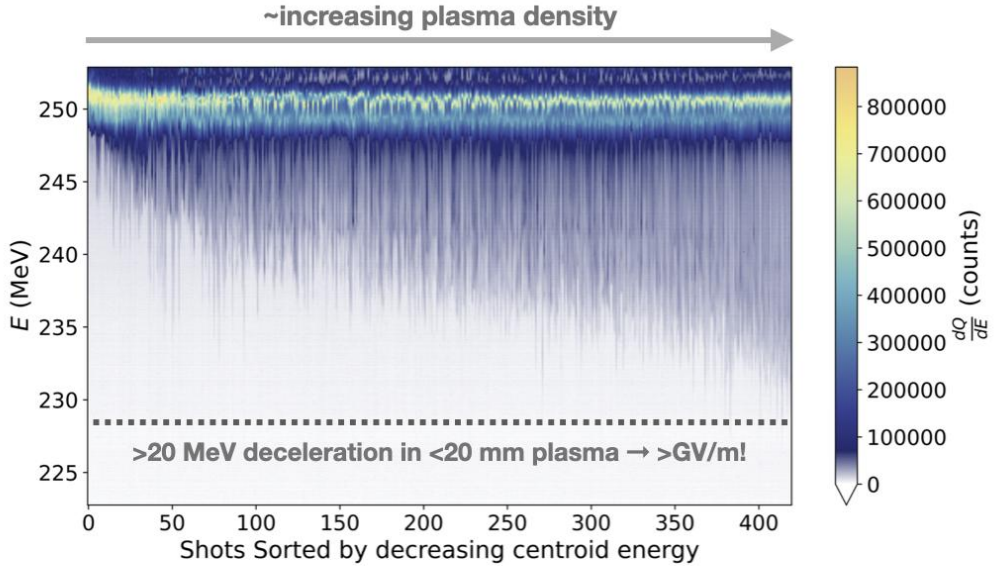
Plasma Acceleration - Results

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

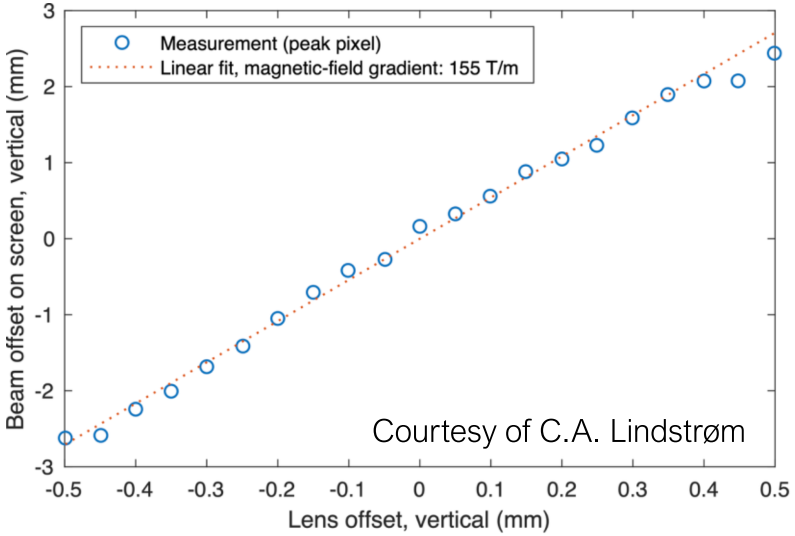
- **All goals achieved!**
  - ✓ ~GV/m electric fields
  - ✓ ~150 T/m magnetic fields

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**



>20 MeV deceleration in <20 mm plasma → >GV/m!



Courtesy of C.A. Lindstrøm

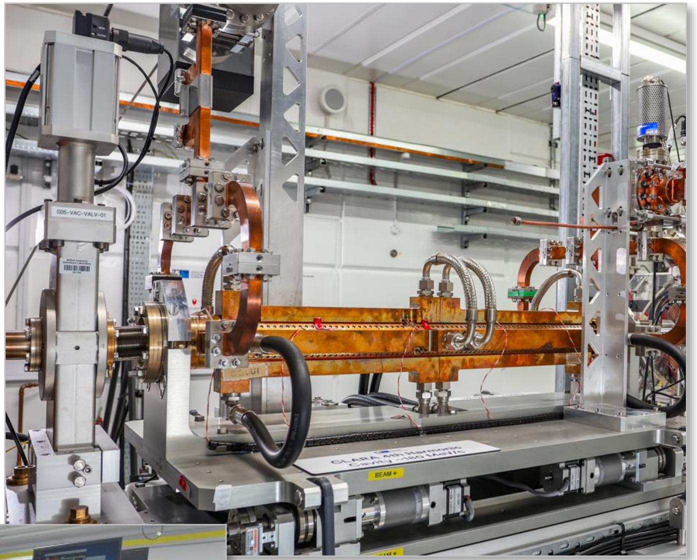
Future Plans

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

More milestones are expected over the coming months…

- ✓ Beam commissioning with 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: X-band linearizer cavity installed on the CLARA beamline

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

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Thank You for Listening!

Questions are Very Welcome

CLARA at IPAC26

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$_2$Te cathode production (*H. Churn*)
THP2144	High-power RF conditioning (*A. Gilfellon*)

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Backup Slides

CLARA Electron Beam Parameters

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

Parameter	**Commissioning**		**Machine Development**	
	High Charge	Low Charge	High Charge	Low Charge
Beam Energy E [MeV]	250	250	250	250
Bunch Charge Q [pC]	250	5	250	5
Bunch Length σ_t [fs]	100	50	$\lesssim 50$	$\ll 50$
Energy Spread σ_E [%]	< 5	< 1	1	0.1
Beam Size [μm]				
σ_x	100	20	50	~1
σ_y	100	20	50	~1
Normalised Emittance [μm rad]				
$\varepsilon_{n,x}$	5	2	< 5	< 1
$\varepsilon_{n,y}$	5	2	< 1	< 1

Above: Full table of expected beam parameters at the FEBE Interaction Point (IP). Parameters for included for initial beam commissioning, and following future Machine Development (MD) periods.