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Introduction to CLARA

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On behalf of the CLARA team

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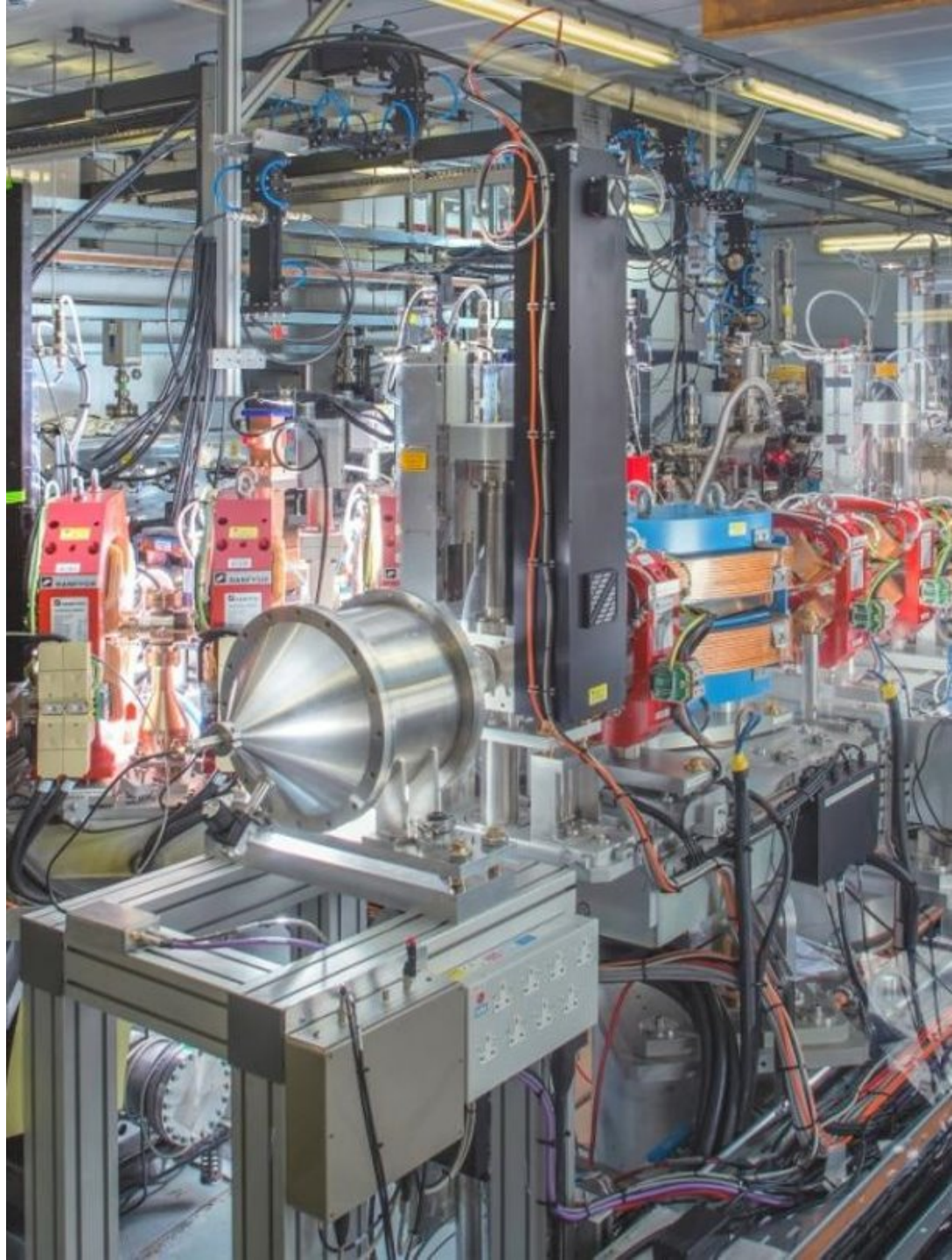

CLARA

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What is CLARA?

- 250 MeV **high-brightness** electron linear accelerator facility [1,2]:
  - Up to **100 Hz** repetition rate
  - Up to **250 pC**
  - Bunch lengths down to **few 10s fs**
- Test-bed for:
  - **Advanced** acceleration techniques
  - VHEE **radiotherapy**
  - Novel **beam diagnostics**
  - Phase space **manipulation**

Timeline

Year	Milestone
2012	CLARA FEL design published [3]
2013 – 2016	VELA gun test stand commissioning (5 MeV/c) [4]
2017	CLARA front end & 400 Hz S-band gun installed
2017 – 2020	CLARA front end commissioning and user experiments (35 MeV/c) [1]
2021 – 2024	CLARA & FEBE installation [2]
2025 – present	CLARA/FEBE technical & beam systems commissioning (250 MeV/c)
2026 – present	User experiments


CLARA Gun


S-band Linac


Arc to FEBE hutch


FEBE hutch

First Commissioning Results

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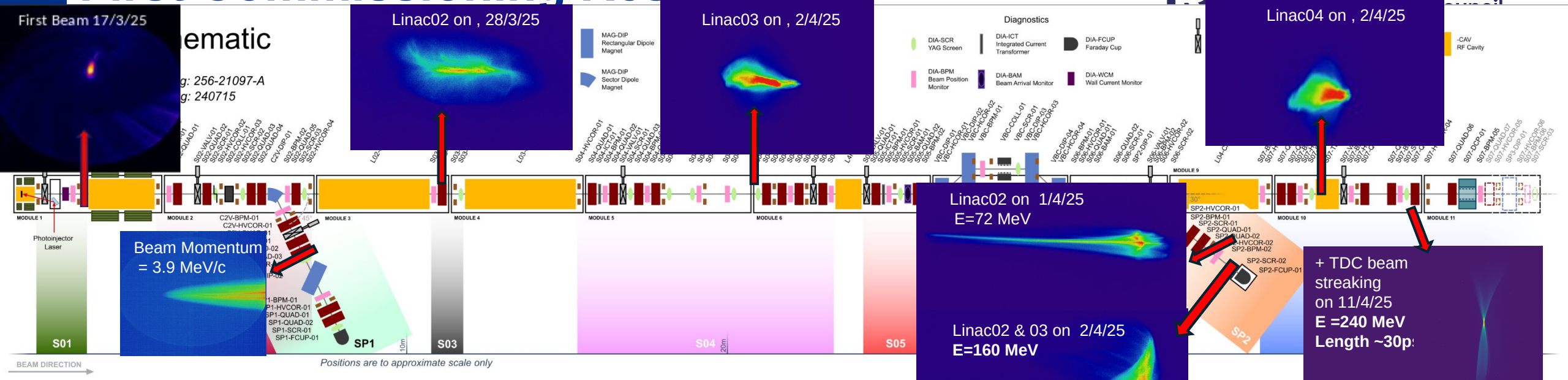
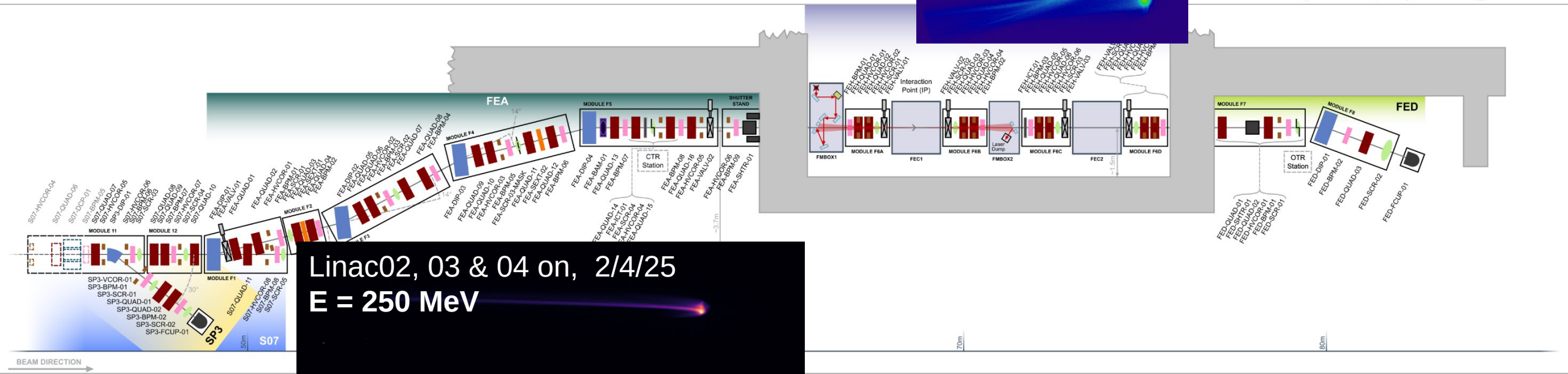


Document source: https://projects.astec.ac.uk/CLARAManual/index.php/CLARA_Control_Room_Resources

For
Emily Shackleton, emily.shackleton@stfc.ac.uk

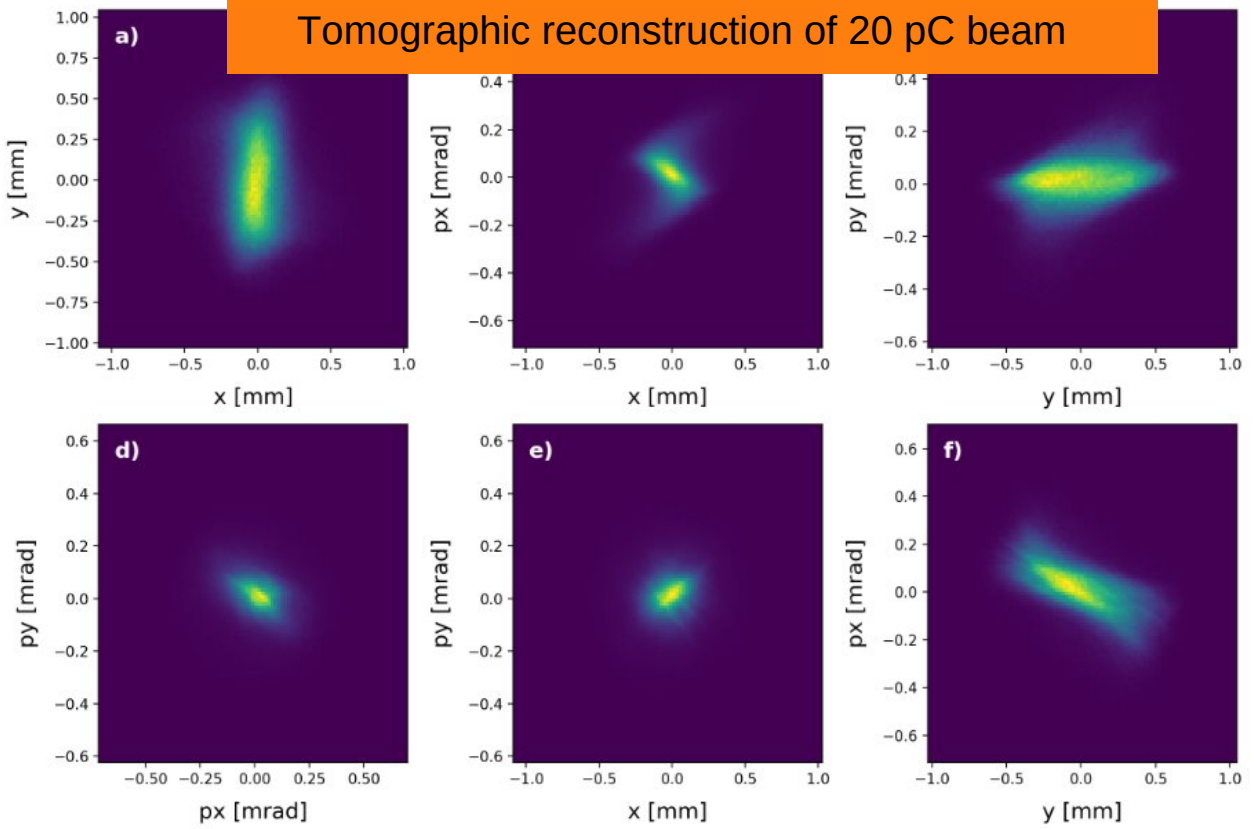


Phase Space Tomography

4D Reconstruction

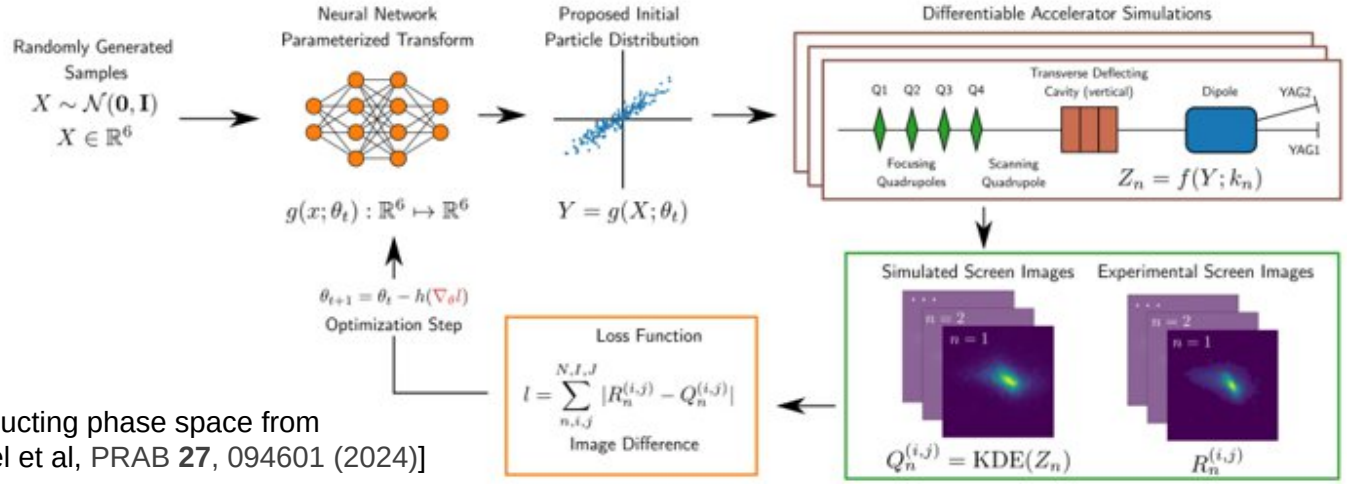
- **4D phase space tomography** has been used to characterize the CLARA beam along the linac [5]
- **Generative phase space reconstruction** (GPSR) has been used as the analysis method [6]
- By using **differentiable simulations**, a neutral network can be trained to **learn** the phase space

Tomographic reconstruction of 20 pC beam



Measured beam parameters at injector exit (250 pC)

Parameter	Horizontal	Vertical
Twiss $\alpha_{x,y}$	-3.59	-4.23
Twiss $\beta_{x,y}$ [m]	22.0	33.6
Emittance [μm]	0.70	0.72



GPSR method for reconstructing phase space from experimental data [Roussel et al, PRAB **27**, 094601 (2024)]

Digital Twin

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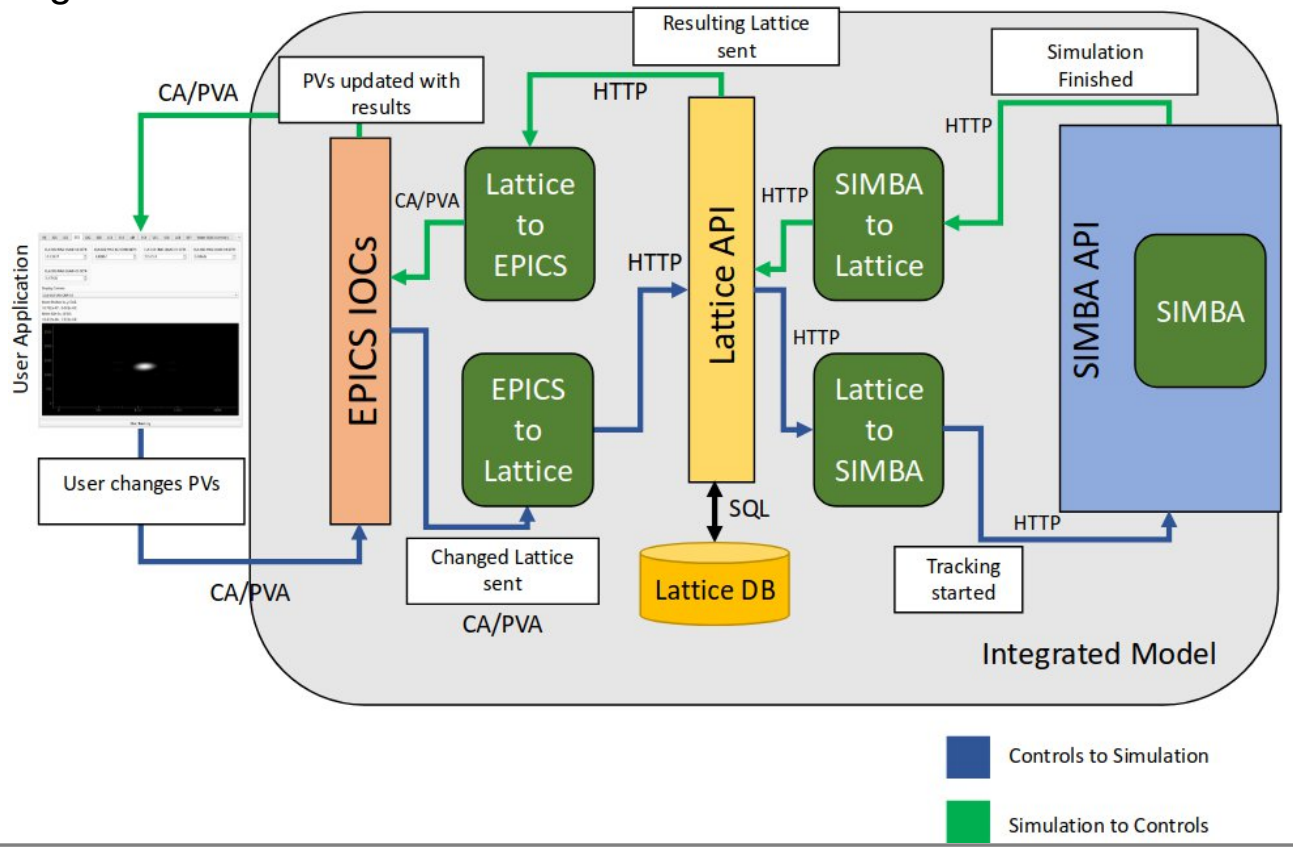
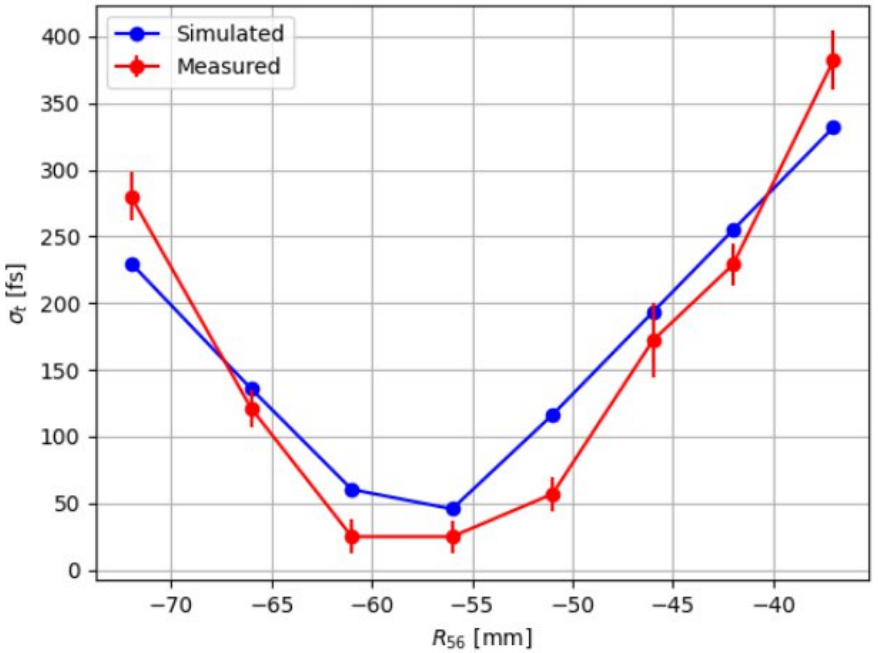
Architecture

- A **digital shadow** has been developed and validation has begun.
- **Virtual control system** is updated based on **real machine settings**.
- This is fed into a **simulation / ML model** which updates virtual diagnostics.



Validation

- Initial comparisons between **real** and **virtual** diagnostics are **promising**.
- Can be used to **train ML models**, and eventually for **offline ML** (**RL**) **optimisation**



Comparison between measured and virtual bunch length

First User Experiments (Preliminary Results)

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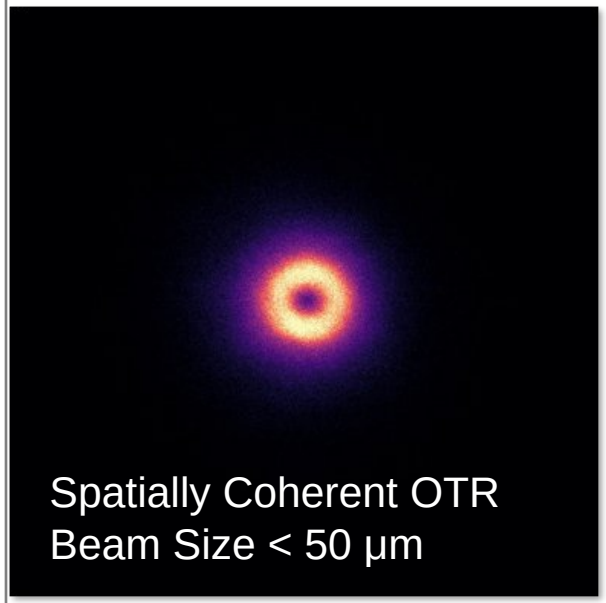
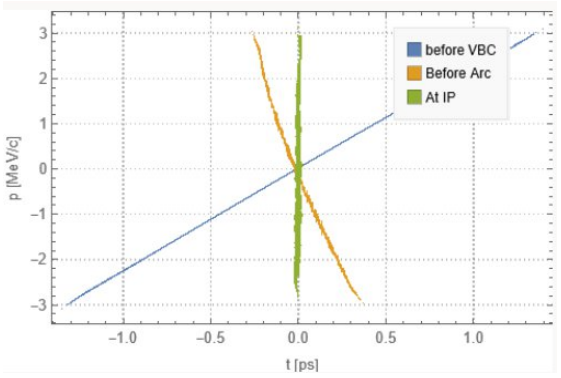
Transverse Diagnostics
U. Liverpool

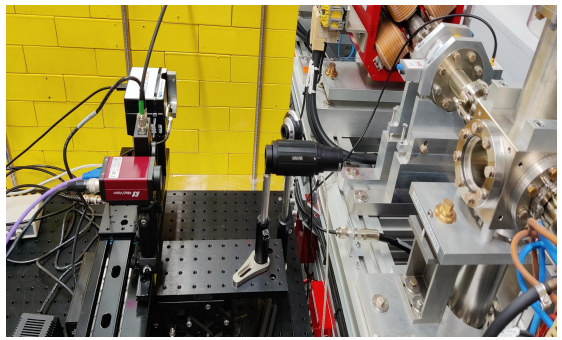
- An emittance diagnostic based on a **single-shot pepper-pot** using OTR has been tested.
- Transverse beam sizes were measured **far below** the resolution of CLARA YAG screens.



Bunch Length Diagnostics
DESY

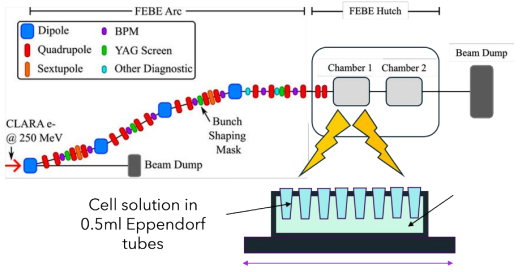
- Novel **low-charge diagnostics** based on **CTR** were installed and tested across a range of bunch lengths.

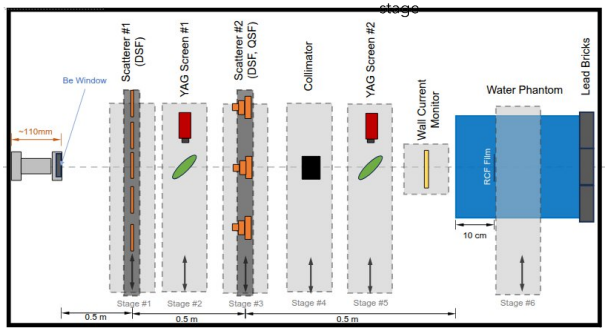




VHEE Radiotherapy
U. Manchester, CERN

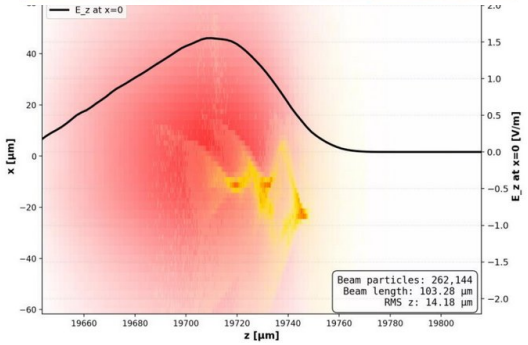
- Biological samples were irradiated with varying dose rates to quantify **cell survival rates**.
- First **VHEE FLASH radiotherapy** in Europe!





Plasma Acceleration
U. Oxford, JAI

- A discharge-capillary-based plasma module is to be installed to enable studies of **non-linear plasma lensing**.
- Will be useful to inform the proposed **HALHF** facility



Future Plans – Commissioning

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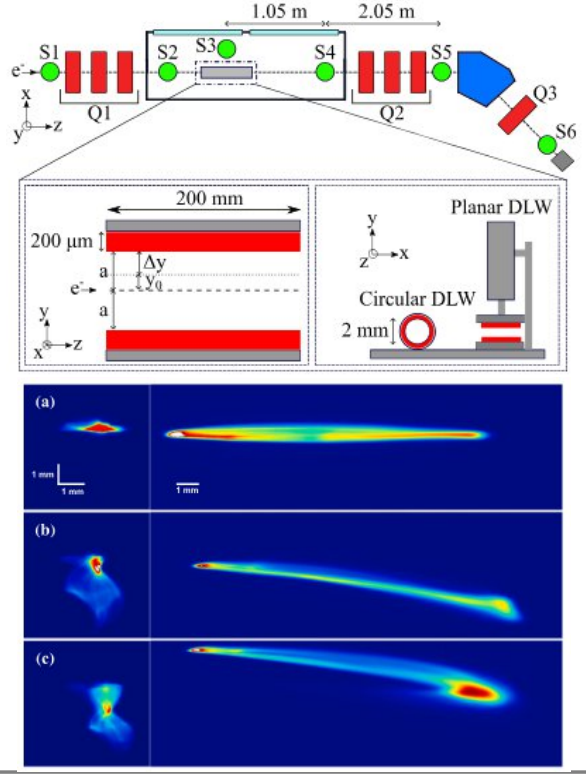
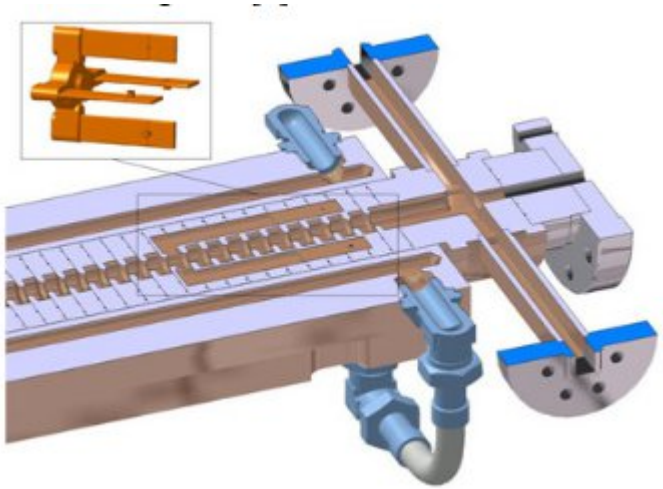
Phase Space Manipulation

- A **passive dielectric dechirper** is being commissioned [8].
- This offers an alternative to RF-based deflectors for **measuring and controlling** the longitudinal phase space



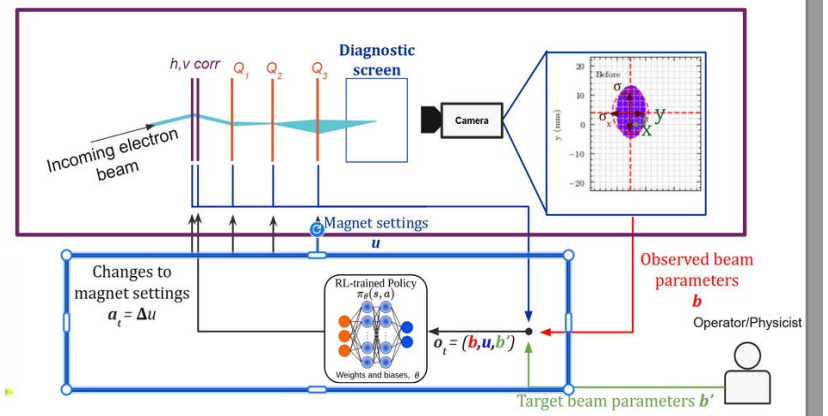
Beam Characterization

- Numerous systems are undergoing **technical commissioning**.
- Full control over the beam phase space requires the 4th **harmonic RF cavity** to be conditioned [9].



Automation

- With the **digital shadow** deployed, we can explore advanced **ML-based tuning** methods to optimize setups offline and develop **predictive diagnostics**.
- **RL tuning** may become crucial for the future operation of CLARA!



Future Plans – Commissioning & Users

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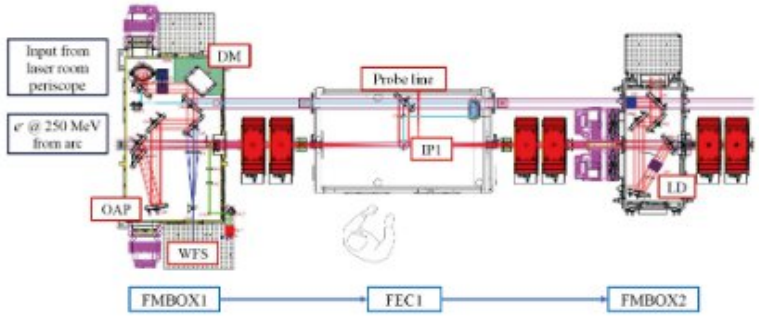
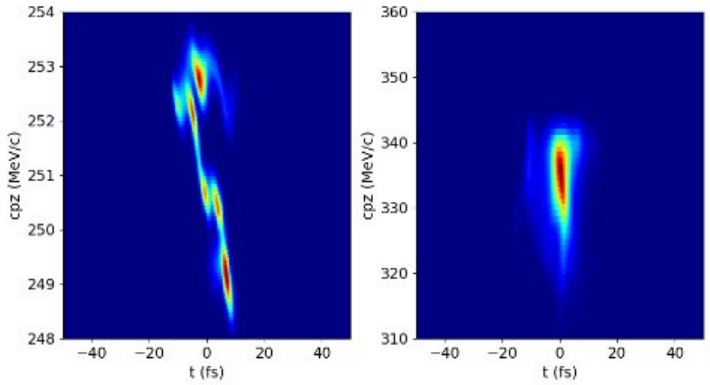
Terawatt Laser

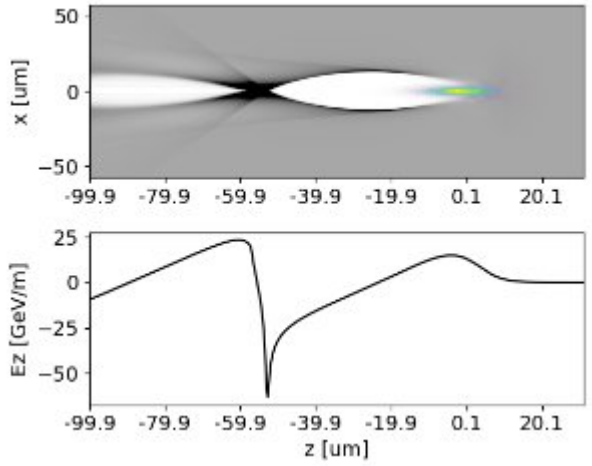
- A **100 TW** (~25 fs) laser is undergoing initial commissioning [2].
- This is to be used to explore laser-based **plasma wakefield acceleration** and ionization.





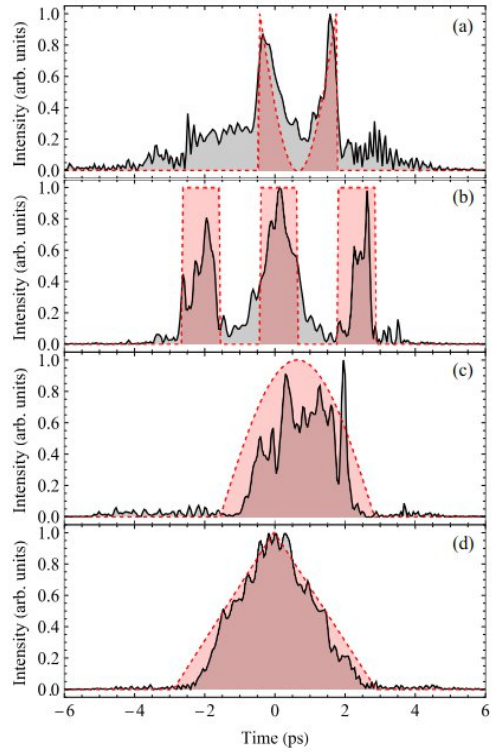
Plasma Acceleration

- **Beam**- or **laser-driven plasma wakefield acceleration** will form a large part of the CLARA user programme.
- The FEBE chamber can accommodate a **range** of possible **plasma experiments**.



Beam Profile Shaping

- Dual beams in a **drive-witness configuration** can be produced via a mask.
- **ML methods** can be used to modulate the photoinjector laser to produce **arbitrary pulse shapes** [10].



Summary

Summary

- CLARA technical systems commissioning at **full beam energy** is underway, indicating good quality **high-brightness beams**.
- Friendly **user program** (Jan – Apr) has been **successful** so far!
- Further commissioning work to do:
  - Bunch compression **linearization** with **4th harmonic cavity**.
  - **Dielectric dechirper** commissioning.
  - Deployment and training of **digital twin**.
  - **TW laser** commissioning for future user programs.

Acknowledgements

Many thanks to the entire CLARA team for delivering a successful installation, promising initial commissioning results and a flourishing user programme!

References

[1] Angal-Kalinin et al, PRAB **23**, 044801 (2020)

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[5] Wolski et al, PRAB **25**, 122803 (2022)

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[7] Foster et al, New J. Phys. **25**, 093037 (2023)

[8] Overton et al, NIM A, **1072**, 170160 (2025)

[9] Cowie et al, Proc. IPAC'18, THPAL084 (2018)

[10] Pollard et al, Proc. IPAC'23, THPL034 (2023)