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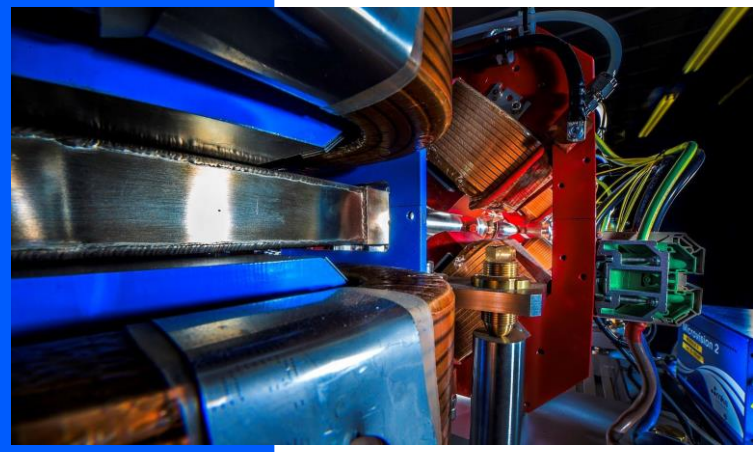
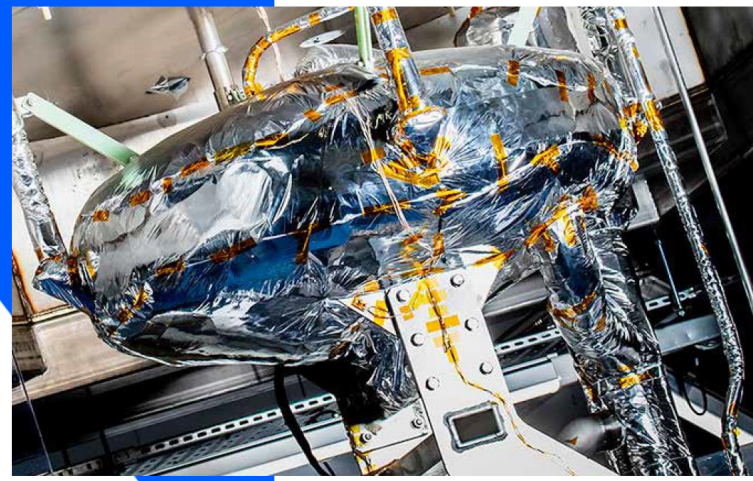
Making a brighter future through advanced accelerators

CLARA as an Accelerator Test Facility for the UK





Deepa Angal-Kalinin on behalf of the CLARA Team

25th July 2022

IoP PAB Conference, Liverpool, 25-26th July 2022

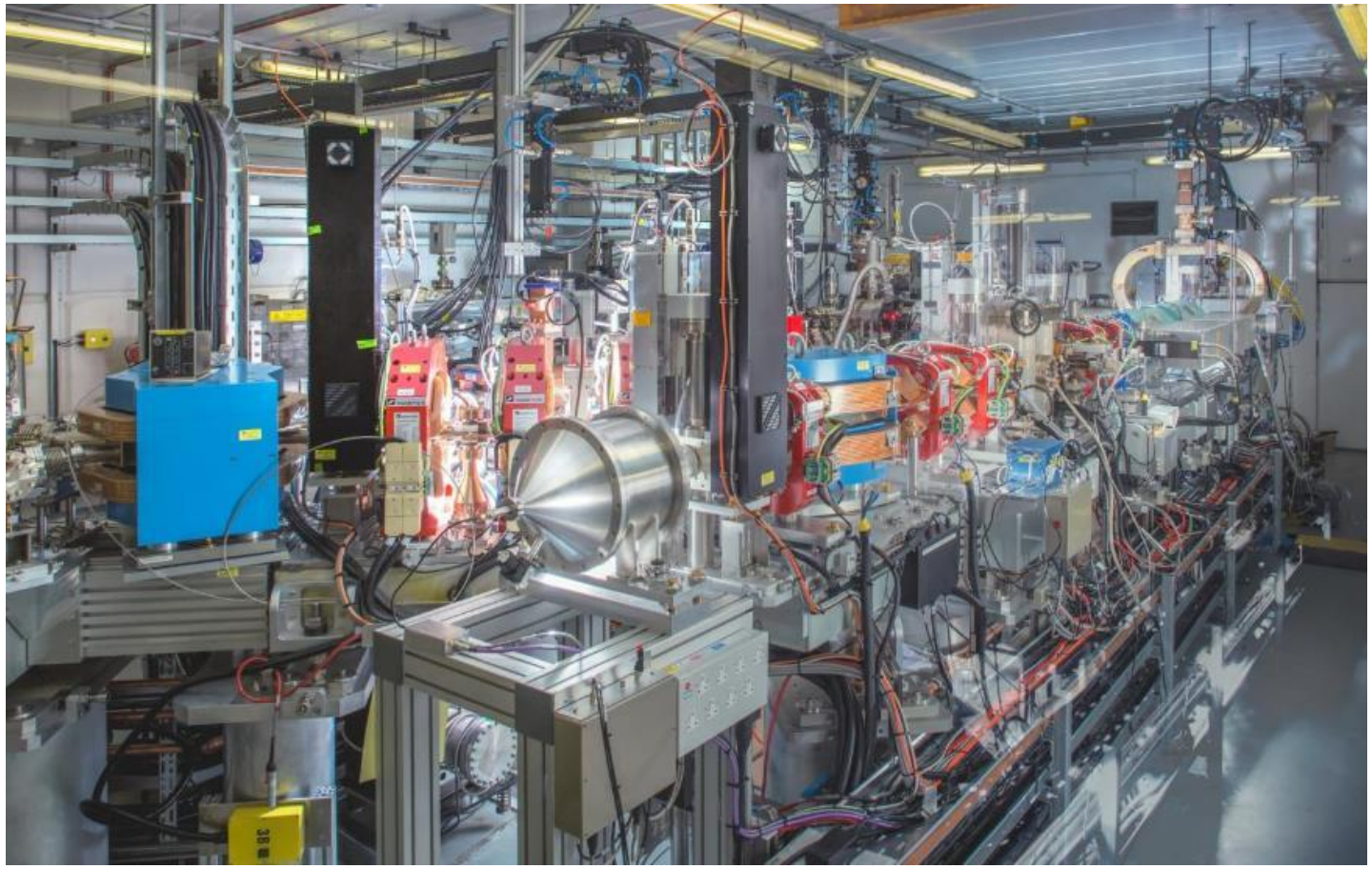
Contents

- Introduction to CLARA
- Phases of CLARA
- Exploitation on CLARA Phase 1/VELA line
- Status of CLARA Phase 2
- Summary

Compact Linear Accelerator for Research and Applications

- CLARA is a high brightness electron test facility enabling the broad range of accelerator and FEL R&D necessary to ensure a future UK XFEL facility is world leading
- Addressing many scientific and technology challenges for future large scale facility
- Establishing key technologies in the UK
  - Photoinjectors and photocathodes
  - Novel undulators
  - New accelerating structures
  - Advanced single bunch diagnostics
  - Machine learning
  - …….
- Flexible test facility to demonstrate novel concepts.

Accelerator Hall Configuration until 2023



CLARA and VELA Accelerator Hall

- **VELA (Versatile Electron Linear Accelerator)**
  - Photoinjector incorporates dedicated diagnostics suite
  - Beamline delivers beam two beam areas (BA1 & BA2)
- **CLARA Front End**
- VELA & CLARA photoinjectors share the same RF and laser infrastructure.
  - ALPHA-X gun (S-Band, 10 Hz)
  - HRRG (S-Band, 400 Hz)

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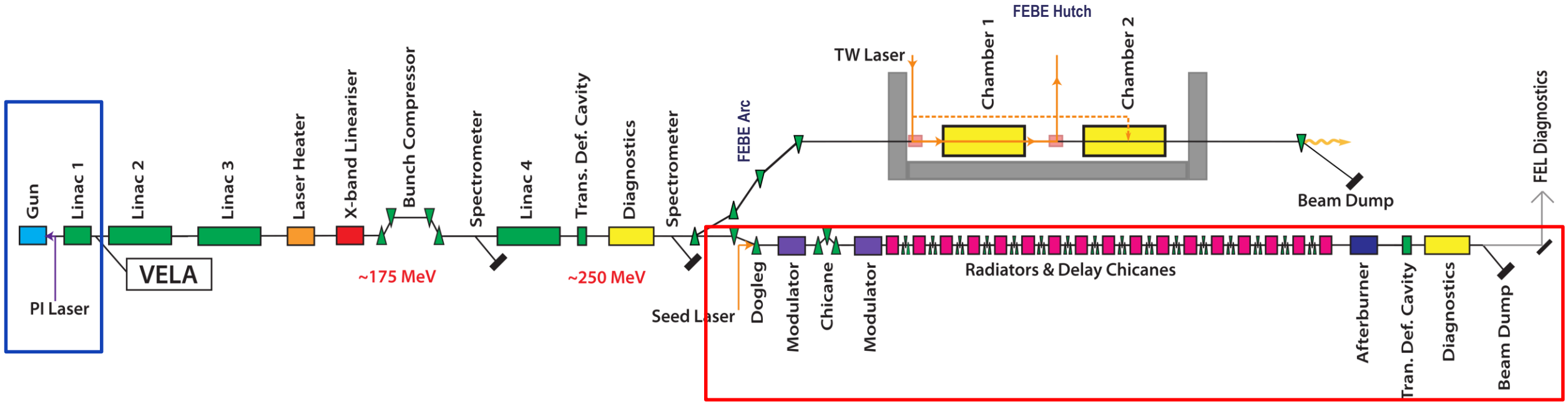
CLARA Schematic & Project Phases



PHASE 1:
50 MeV, 250 pC at 10 Hz ACHIEVED (2017)

PHASE 2:
250 MeV, ASSEMBLED OFFLINE,
Partly installed in the accelerator hall.

Includes dedicated 250 MeV beamline (FEBE) for novel experiments (approved in 2019 ahead of Phase 3)

PHASE 3:
100 nm FEL
NOT YET FUNDED
Decision tied to UK XFEL

Total length = 95 m

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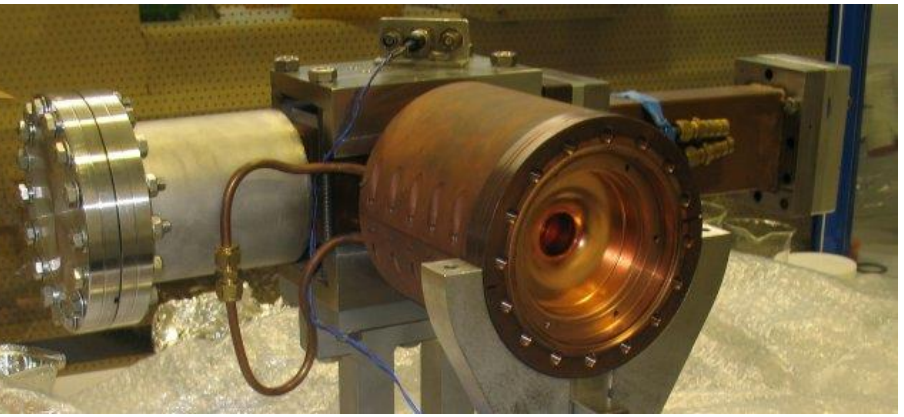
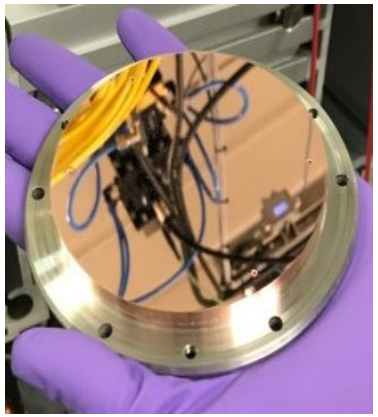
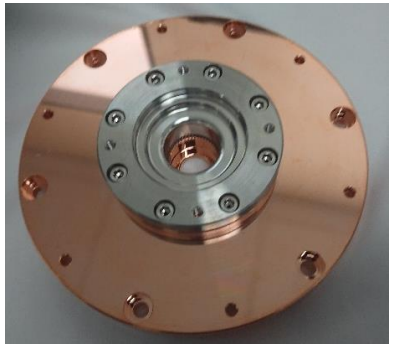
ALPHA-X Gun (10 Hz)





Back wall photocathode

Hybrid Cu/Mo photocathode with off-centre diamond turned tip

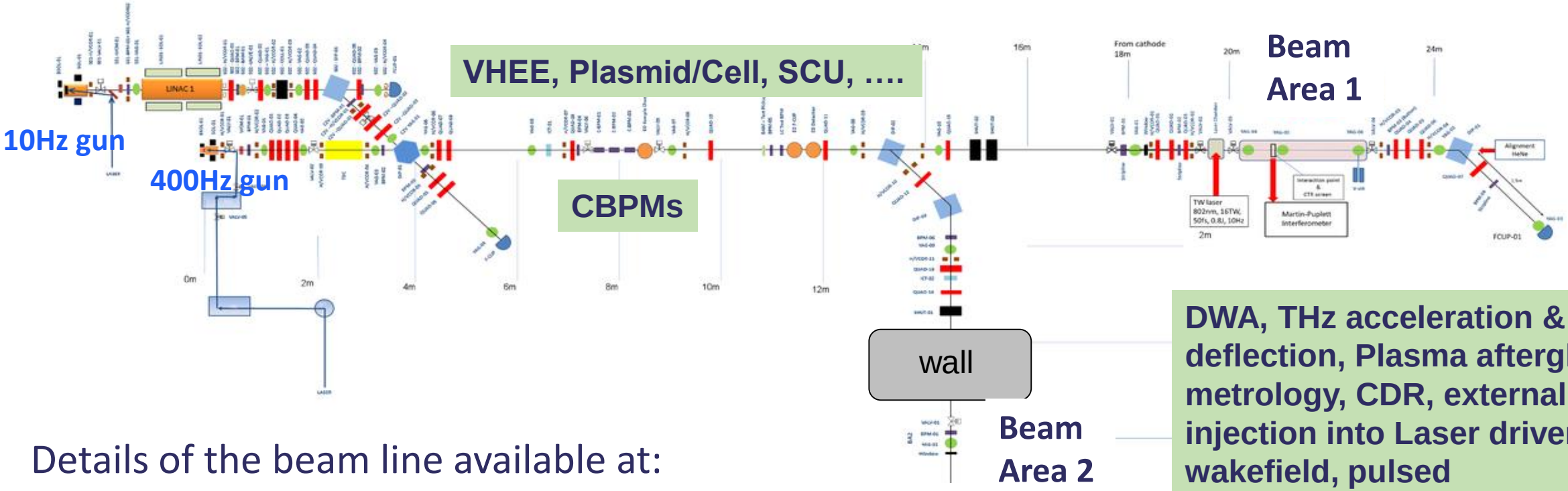


Back wall of the cavity with photocathode socket

- 2.5-cell S-Band RF gun, 10 Hz repetition rate ALPHA-X gun on loan from Strathclyde.
- Commissioned and operated on VELA line from 2013-2016. Swapped to CLARA line in 2017.
- Gun was upgraded to operate with interchangeable photocathode plug in 2019 which allows to transport and swap cathodes without breaking vacuum.
- Back wall Copper photocathode replaced with hybrid Cu/Mo photocathode with off-centred diamond turned tip.
- Major efforts concentrated on improving beam quality and mitigation of dark current.
- Extensive photocathode R&D underpinning programme in dedicated lab space.

CLARA Phase 1 Exploitation Experiments (2018-22)

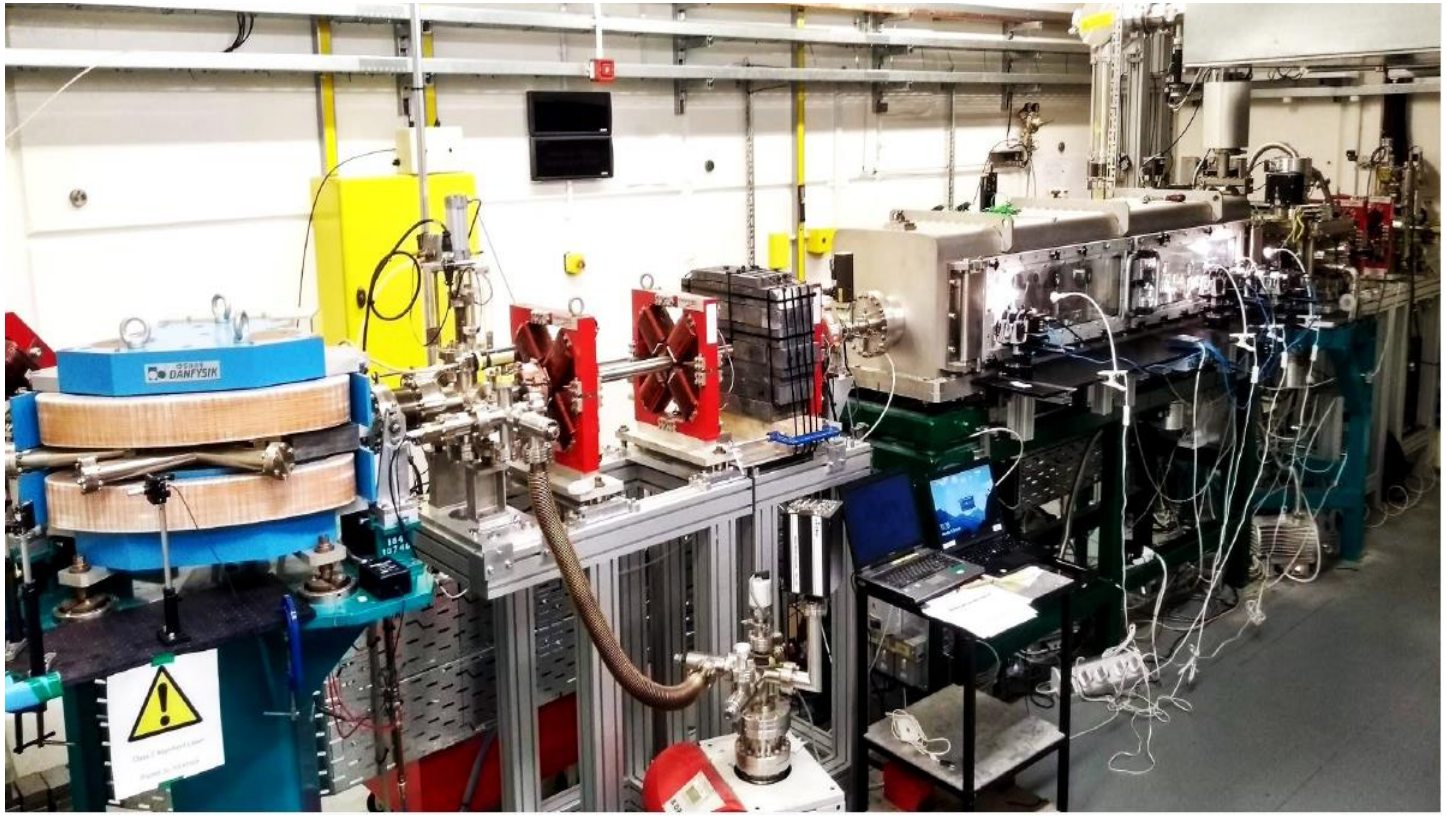
- RF gun + Linac accelerates beam to 50 MeV. S-bend merges beam with the VELA beamline.
- High energy beam delivered to users in two user runs (2018/19 & 2021/22) following competitive beam time allocation process.
- Beam time requests oversubscribed by a factor of two. High demand for BA1 and experiments utilising TW laser.



Details of the beam line available at:

[Angal-Kalinin et al, Phys. Rev. Accel. Beams 23, 044801, 2020]

VELA Beam Area 1



- Electron beam:
  - 35 MeV, 100 pC, 10 Hz
  - 300 fs (RMS) length, 100 µm (RMS) radius
- Laser:
  - ~500 mJ, 50 fs, 10 Hz, synchronized ~100 fs
  - f/19 parabola
- User Chamber:
  - Old SRS ‘empty box’, retrofitted with breadboard and gas/electrical feedthroughs
  - Diagnostics for beam profile – IP & Upstream and downstream of IP
  - Can be pumped down in few hours
- Beam line incorporates spectrometer dipole to measure energy spectra & FCUP for charge measurement.

CLARA User Meeting

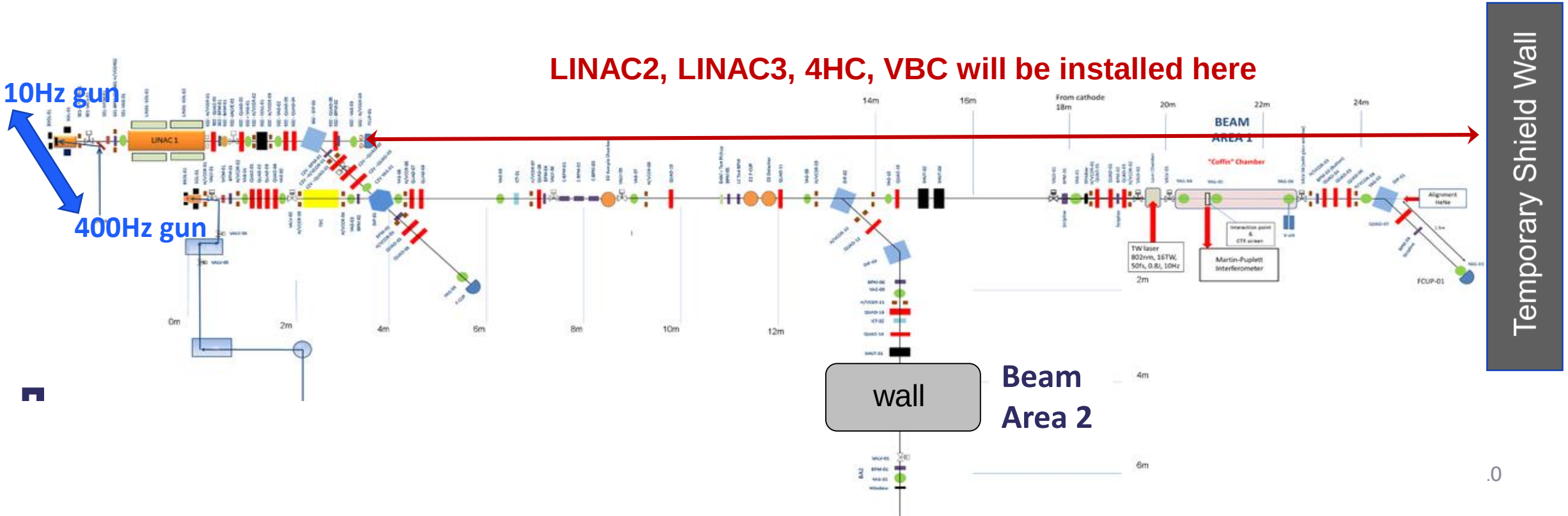
Following successful exploitation run (October'21-April'22), Third CLARA User Meeting was held on 5th of July'22 at Daresbury Laboratory in a hybrid format with 55 participants attending in person and 20 connected remotely.

- All experimental teams presented results from their experiments and outlined plans for publications of their results.
- The CLARA team presented the plans and timeline for completion of Phase 2.
- Detailed presentations available at: https://indico.stfc.ac.uk/event/574/

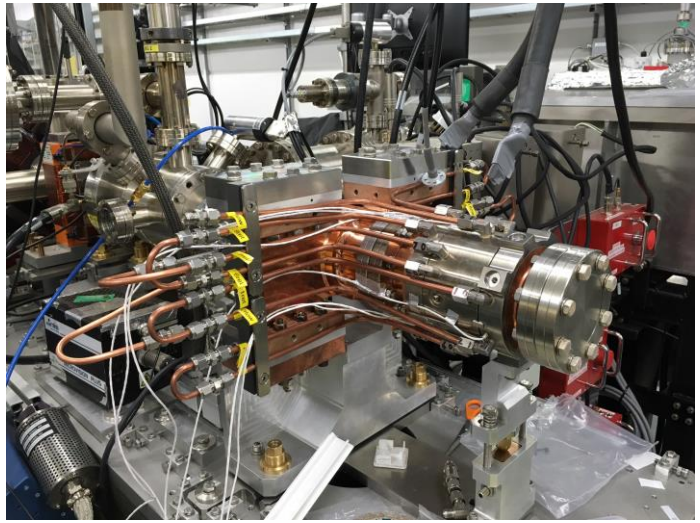
Talks by Morgan Hibberd, Lewis Reid, Toby Overton at this conference.

VELA/CLARA Accelerator Hall & Phase 2

- Temporary shield wall at the end of BA1 allows operation of VELA/CLARA FE whilst installation of Phase 2 continues beyond this wall.
- When Phase 2 beam line will be installed, existing BA1 beamline will not be operational due to component clash (also due to preference not to switch off the accelerator to maintain stable operation).
- Option to move BA1 beamline and TW laser to BA2 has been worked out but is currently not prioritised.



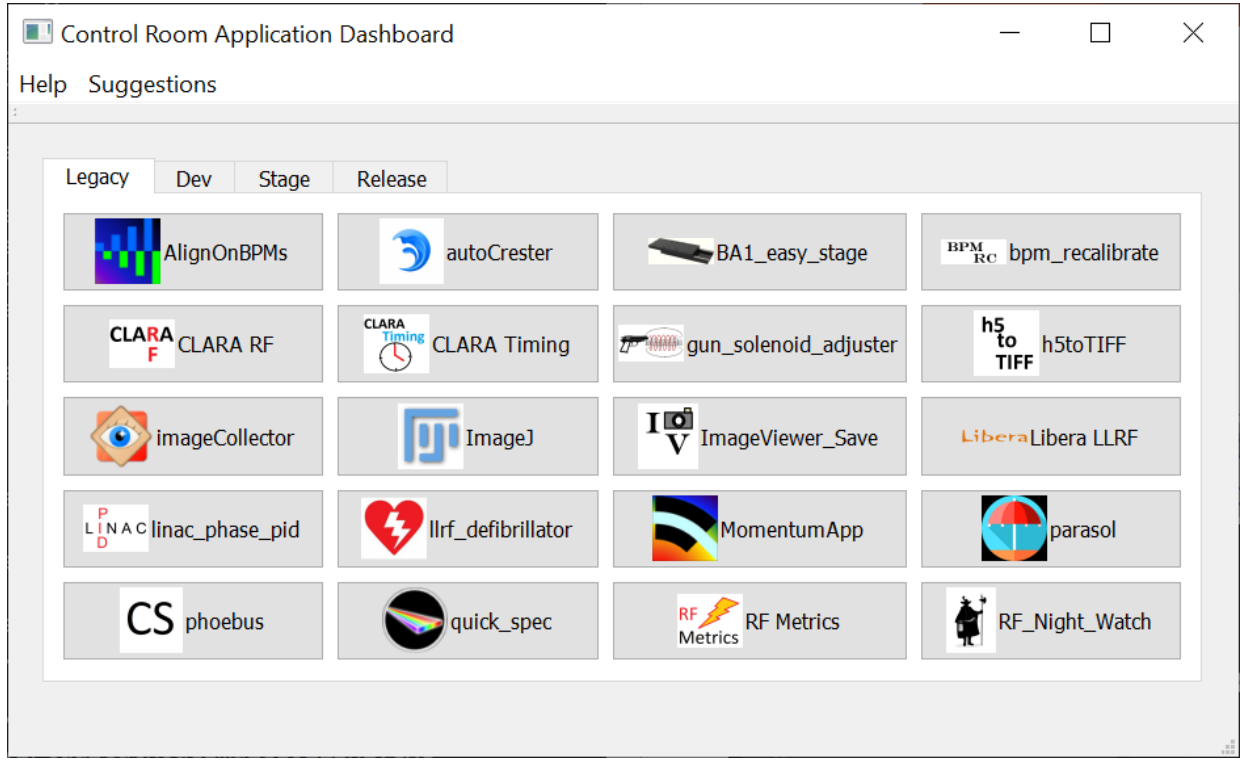
High Repetition Rate Gun (400 Hz)



- 1.5-cell S-band High Repetition Rate Gun (HRRG) designed by STFC/CI/INR collaboration.
- Fitted with vacuum load-lock system which allows to transport and swap cathodes without breaking vacuum.
- Gun installed on VELA line in 2016 shutdown. RF auto-conditioning script developed & tested for unmanned conditioning.
- Time sharing with CLARA line and issues with RF waveguide switch delayed commissioning.
- Conditioning followed by commissioning to start August'22.
- Gun will be swapped to CLARA line from VELA line in 2023.

CLARA Software Tools & Simulations

- Major effort to ensure robustness of control room software.
- All software accessed from Application dashboard, documentation on CLARA wiki
- Work in progress to establish consistency with the online model - will allow seamless comparison of machine status with simulations.
- Number of brand new tools being developed for new diagnostics and for exploitation experiments in collaboration with users.

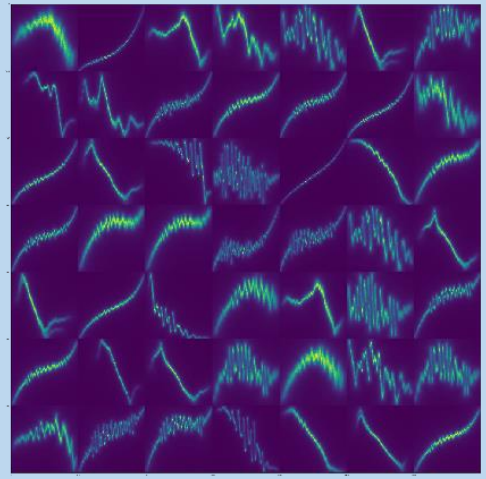


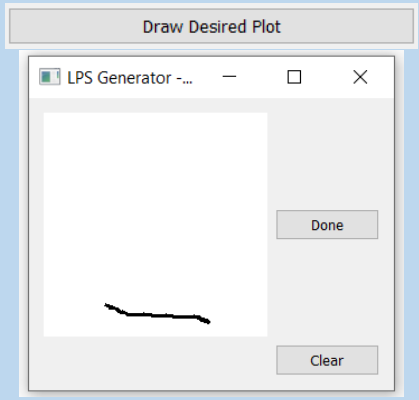
- Effort is now ramping up to apply Machine Learning in several areas on CLARA
- Great potential to use CLARA for application of ML.

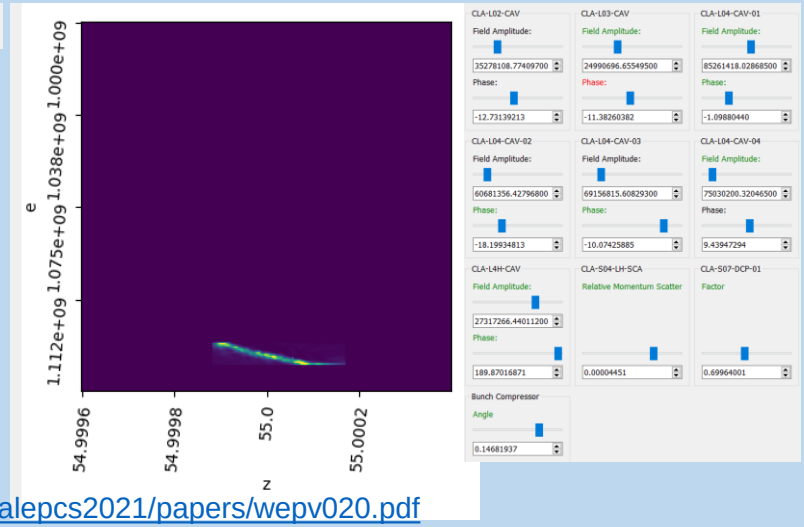
Machine Learning – Custom Bunch Shaping

- We aim to use Machine Learning to deliver an **efficient, automated accelerator** with **rapidly customisable beam properties**.

- Simulation-based example to learn the relationship between accelerator settings and longitudinal phase space:
- Trained using ~10k examples
- Users can draw the desired LPS to get the required machine settings



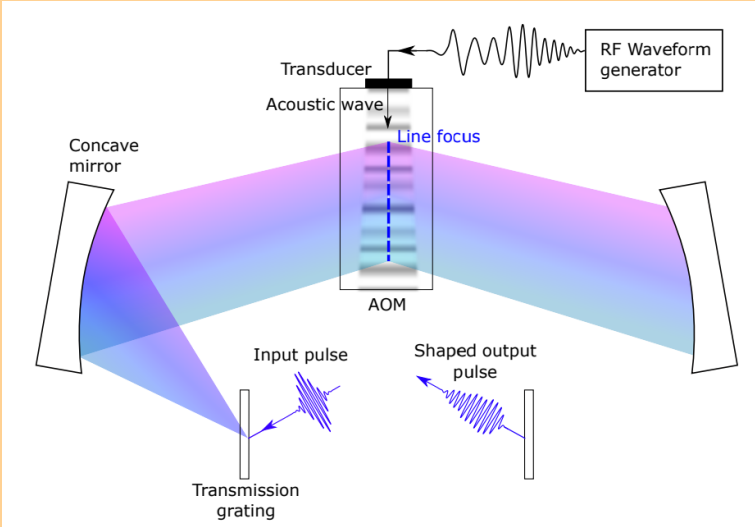




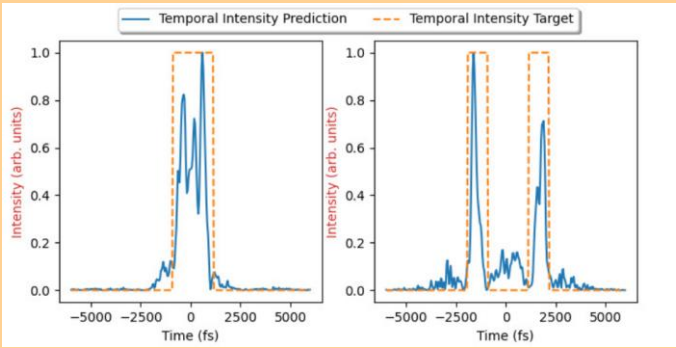
https://accelconf.web.cern.ch/icalepcs2021/papers/wepv020.pdf

- Simulation/experiment-based project to deploy ML-based pulse shaping for the CLARA photo-injector laser:

Schematic of the temporal pulse shaper at CLARA, featuring an acousto-optic modulator (AOM)



Demonstration of solutions found for arbitrary pulse shapes (the model takes into account physical constraints)



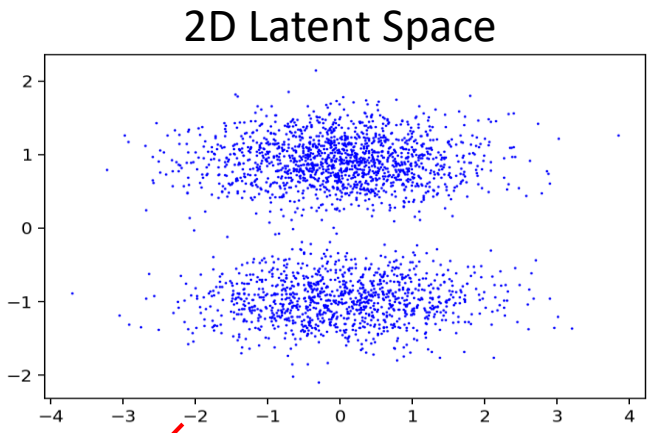
Poster presentation by Amelia Pollard

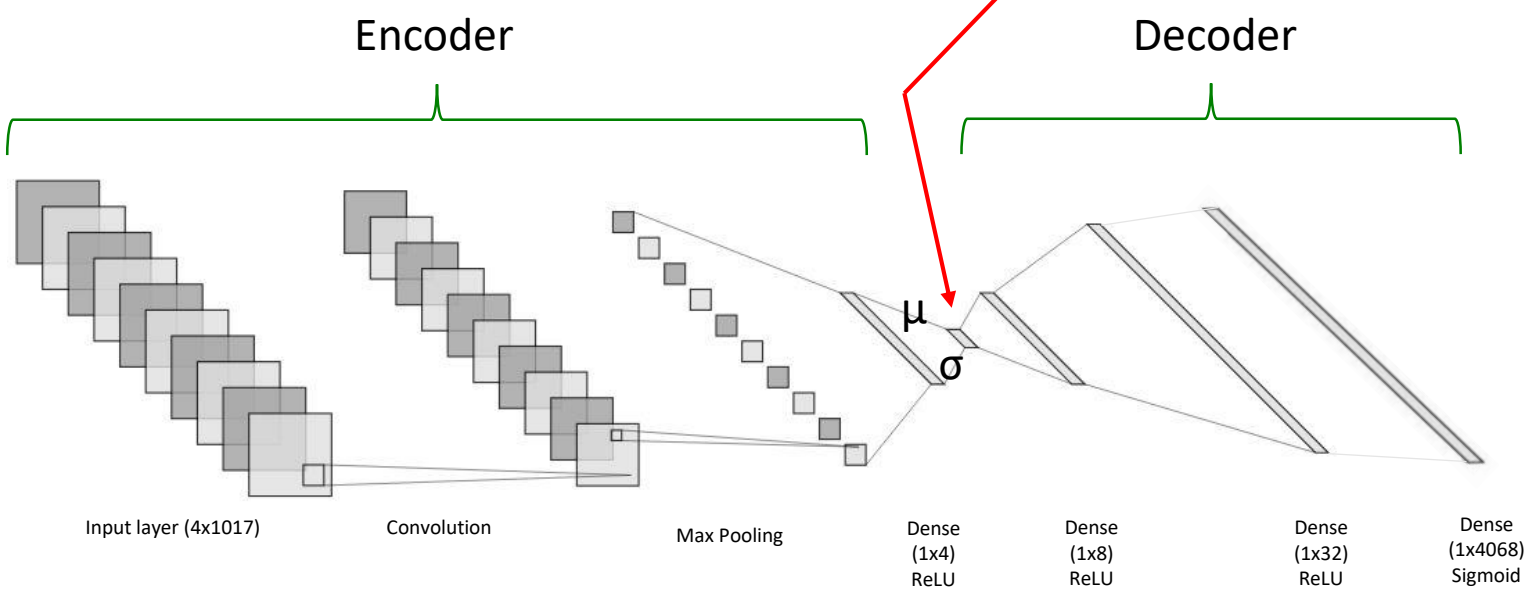
https://accelconf.web.cern.ch/ipac2022/papers/thpotk061.pdf

Machine Learning – RF Breakdown Detection

- Work is ongoing to use machine learning for **improved detection of RF breakdowns**, to be used in HRRG & Phase 2 RF conditioning.

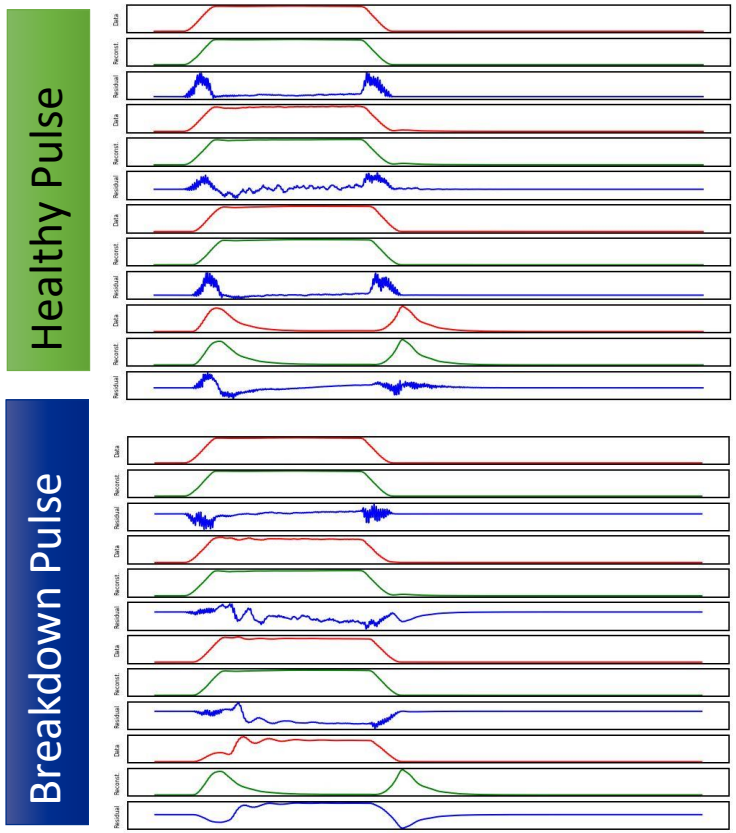
- An anomaly detection method has been used, whereby an autoencoder is 'over-trained' using healthy RF traces.
- When shown a breakdown trace the reconstruction will not match the data.
- High accuracy and recall show it is an effective classifier of breakdowns.





https://accelconf.web.cern.ch/icalepcs2021/papers/wepv021.pdf

Data – **Reconstruction** = **Residual**



There is a UK interest group on machine learning for accelerators – contact: david.dunning@stfc.ac.uk

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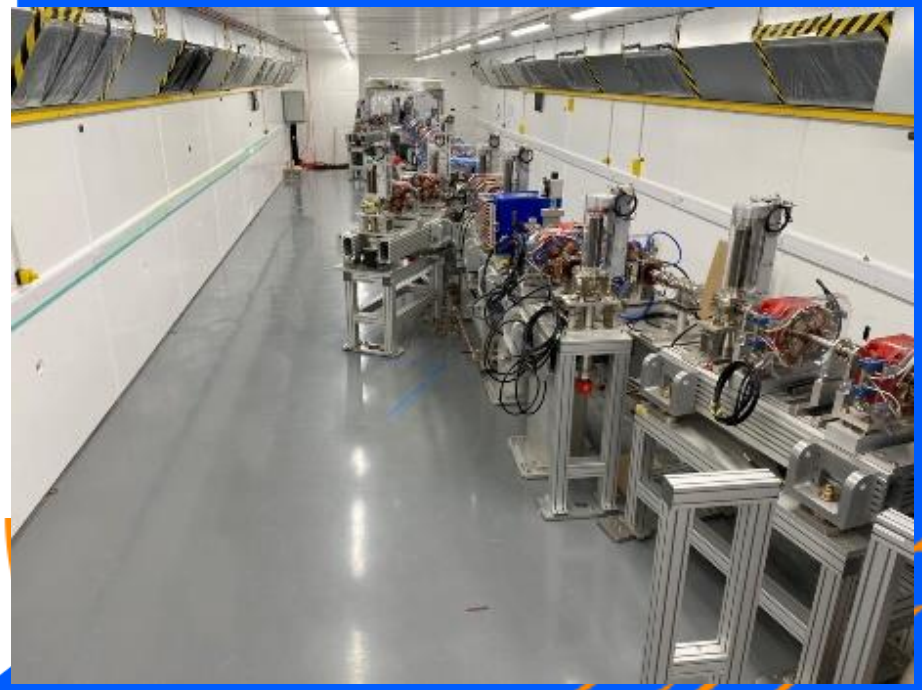
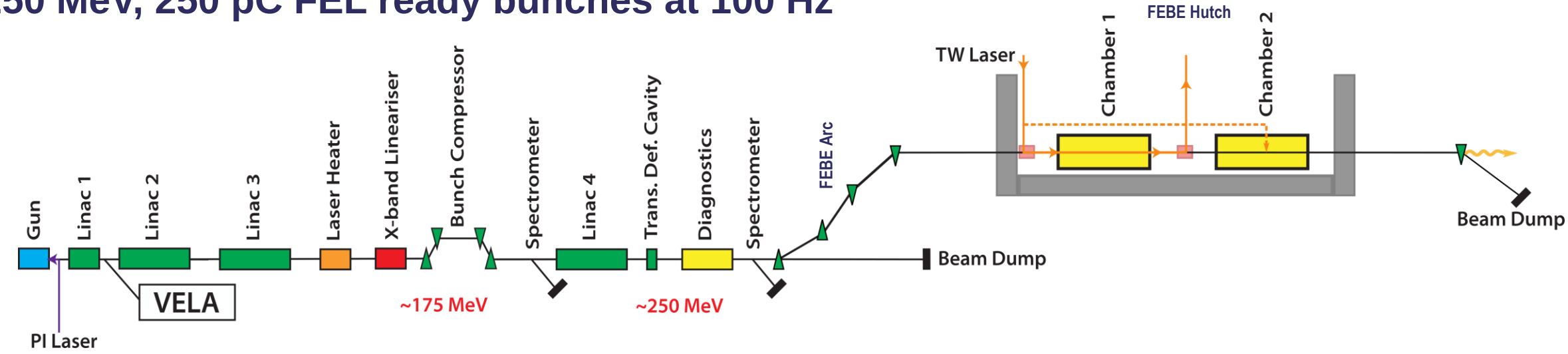
CLARA Phase 2



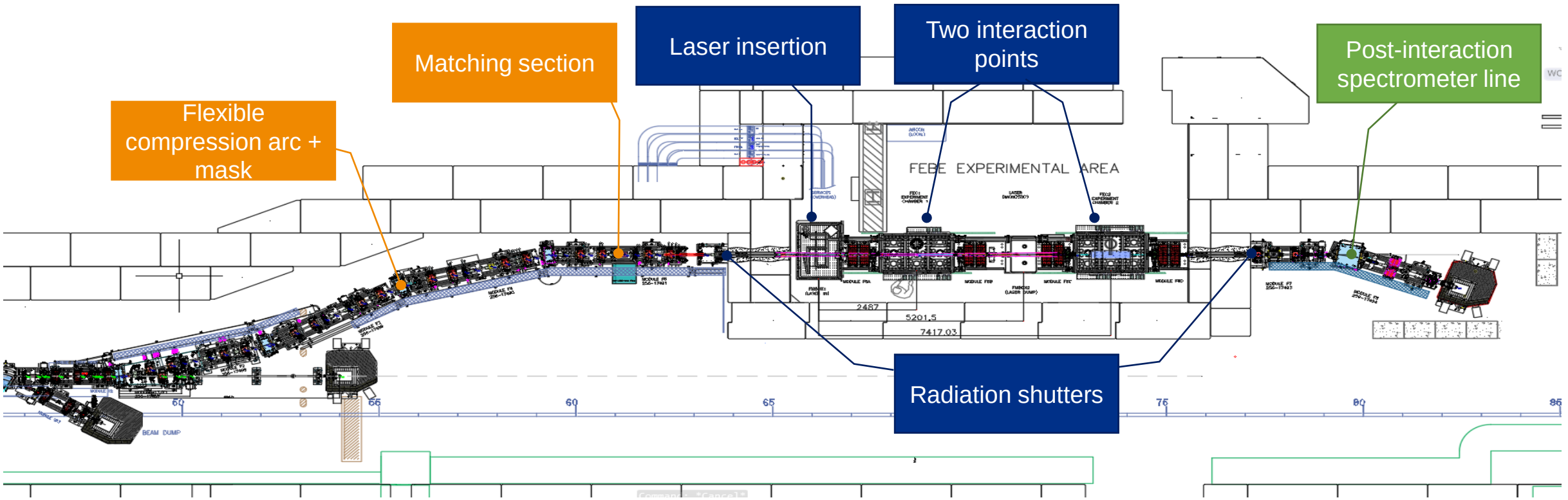
CLARA Phase 2 - Schematic

250 MeV, 250 pC FEL ready bunches at 100 Hz



- Three 4 m long S-band Linacs, Variable Bunch Compressor, X-band lineariser, space reserved for Laser Heater.
- Full 6-D beam characterisation using S-band TDC at 250 MeV.
- Beamline incorporates DWA dechirper (Half of the wakefield energy dechirper tested in BA1)
- Full Energy Beamline for Exploitation (FEBE) delivers beam to dedicated shielded enclosure.

FEBE Design Overview

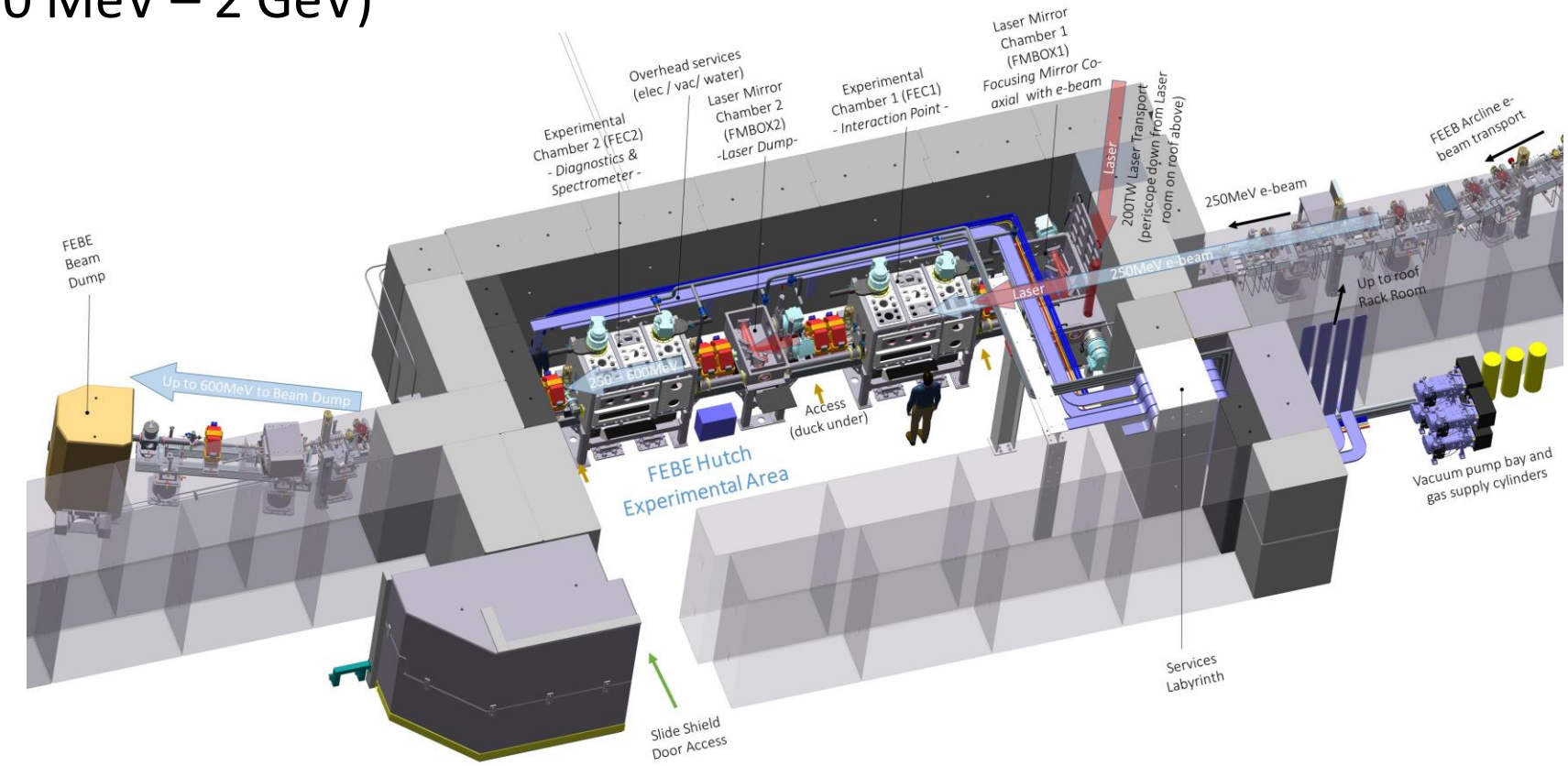


- FEBE design is conceived and developed in collaboration with stakeholders and is building upon the existing community interest and demonstrations on CLARA FE.
- FEBE arc is designed to mitigate CSR
- Dedicated diagnostics pre- and post interaction point to fully characterise beams.

FEBE Hutch Overview

Hutch footprint: 10×5.4×3 m³, Shielding: total beam power 6 W

Flexibility with bunch charge (maximum 250 pC), bunch repetition rate (maximum 100 Hz), beam energy (250 MeV – 2 GeV)



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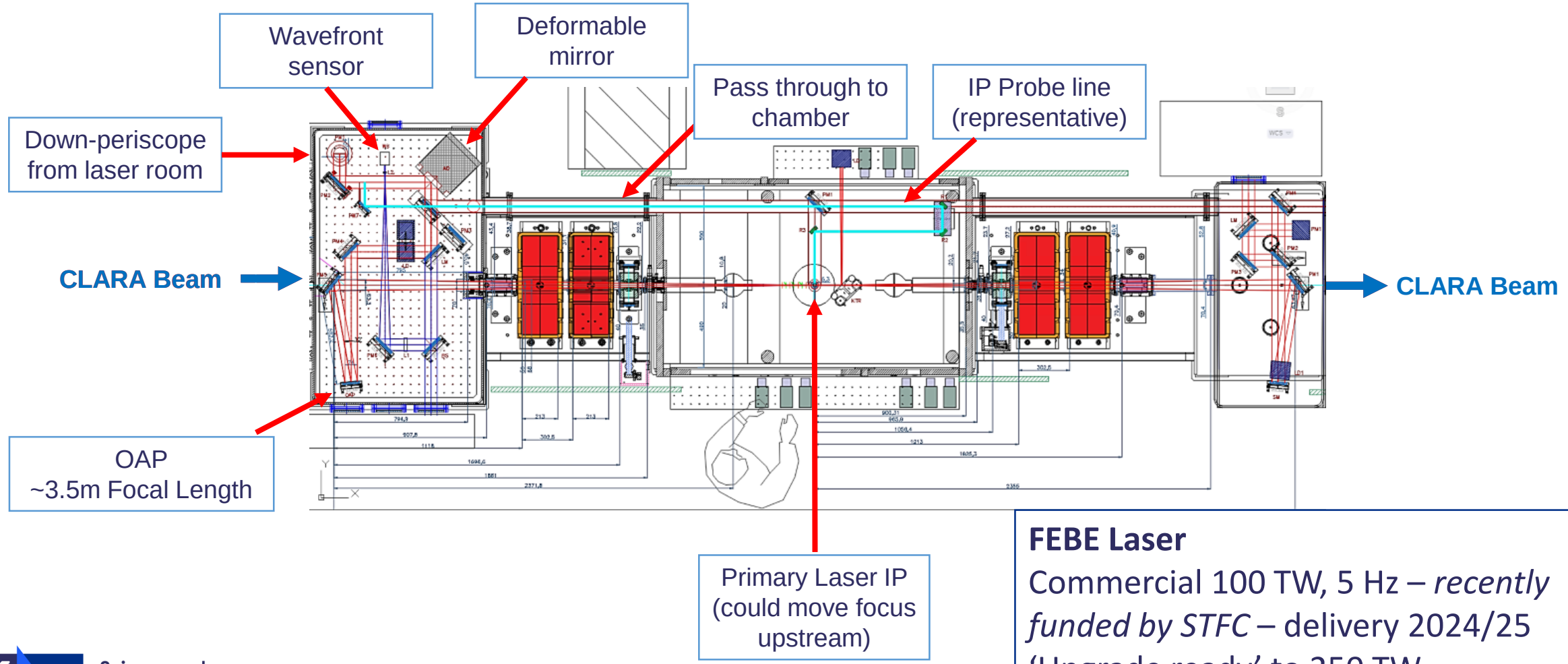
Two identical chambers: more flexible, provides diagnostic support, and a route towards ambitious interaction/transport/application

FEBE Laser



FEBE Laser

Commercial 100 TW, 5 Hz – *recently funded by STFC* – delivery 2024/25

'Upgrade ready' to 250 TW

Femtosecond synchronization to CLARA Optical Timing Network

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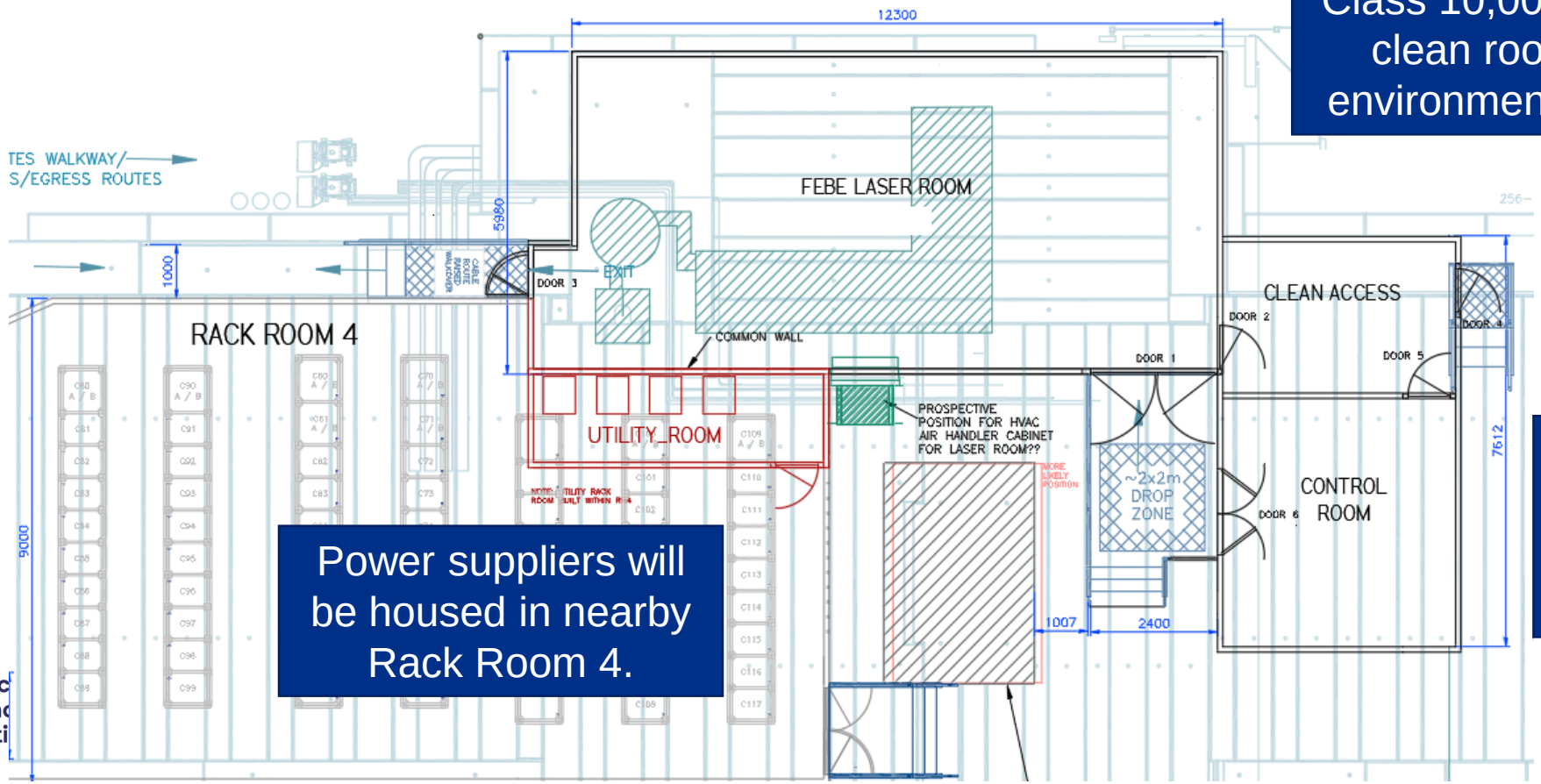
FEBE Laser

Immediately on top of the FEBE hutch to minimise path length to target.

Class 10,000 (ISO 7) clean room with environment control.

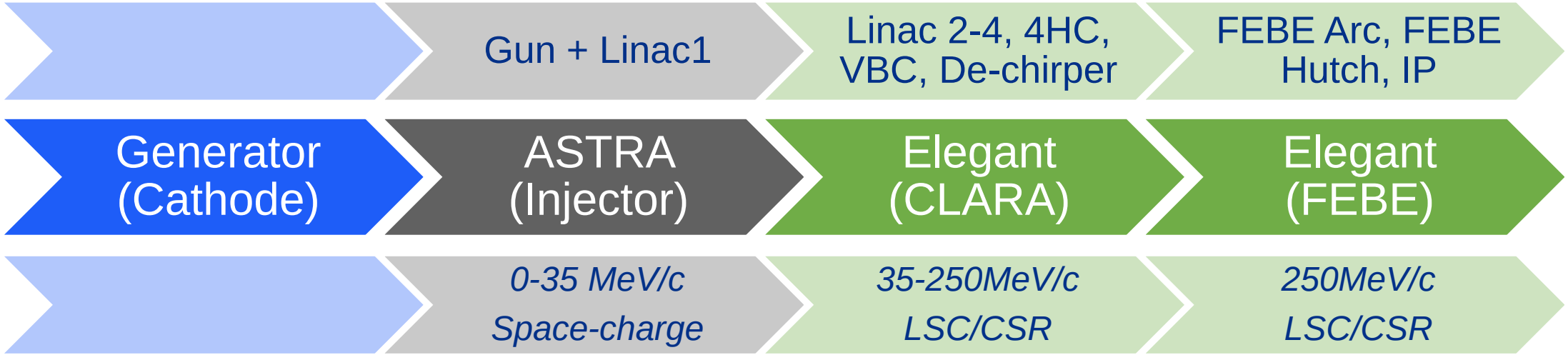


Power suppliers will be housed in nearby Rack Room 4.

Operated from immediately adjacent laser control room.

Tracking Tools

- Tracking performed in SimFrame – ASTRA + Elegant
  - Includes LSC, CSR, Cavity Wakefields, De-chirper Wakefields
  - Optimisation using GA and Simplex
- Strong CSR/LSC effects (low energy, high charge)



Beam parameters

Offered parameters to evolve, based on development time

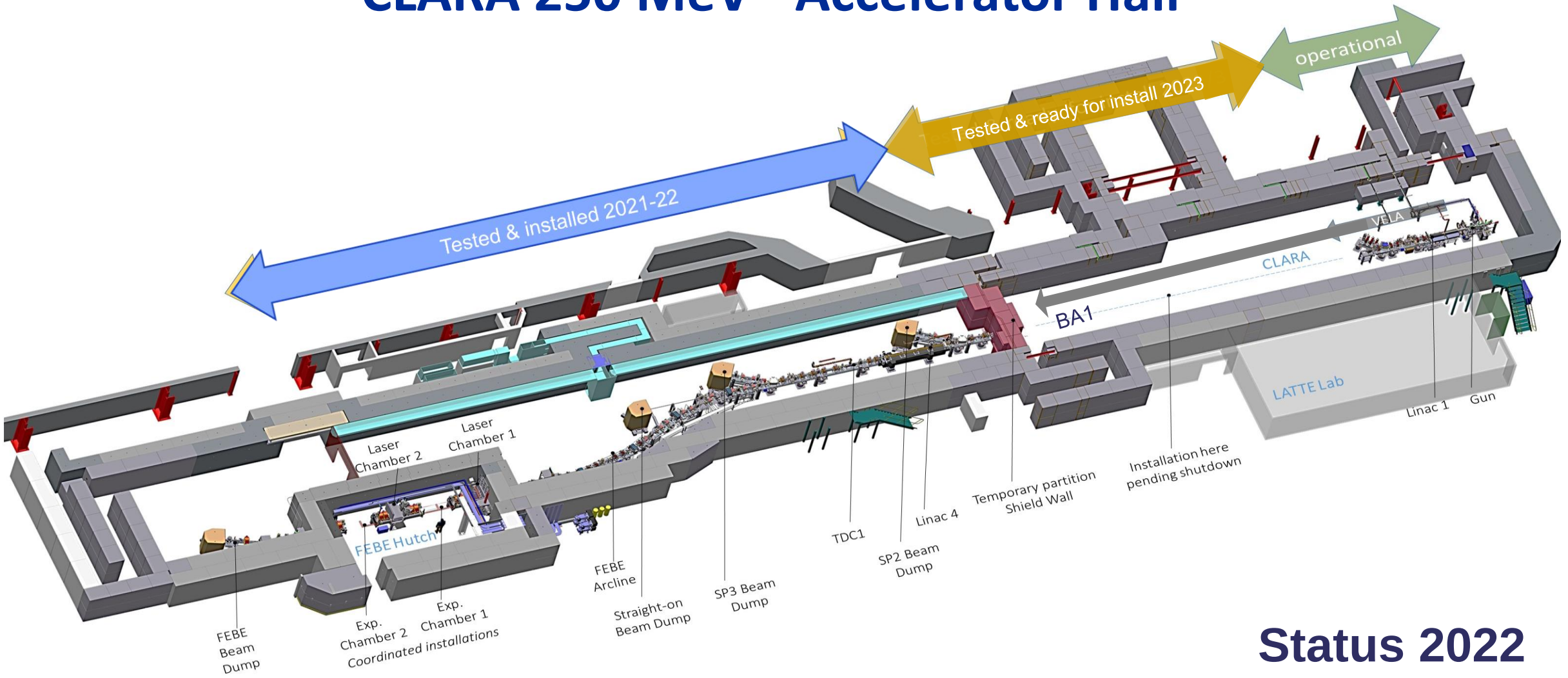
'Day 1' → *Nominal* → *R&D*

Parameter	High charge	Low charge
Energy [MeV]	250	250
Charge [pC]	250	5
RMS t [fs]	100 (50)	50 (≤50)
σ_E/E [%]	<5 (1)	<1 (<1)
RMS x [µm]	100 (50)	20 (1)
RMS y [µm]	100 (50)	20 (1)
ε_N x @ 250 MeV [µm]	5 (<5)	2 (1)
ε_N y @ 250 MeV [µm]	5 (<1)	2 (<1)

All parameters to be confirmed through measurement using appropriate diagnostics.

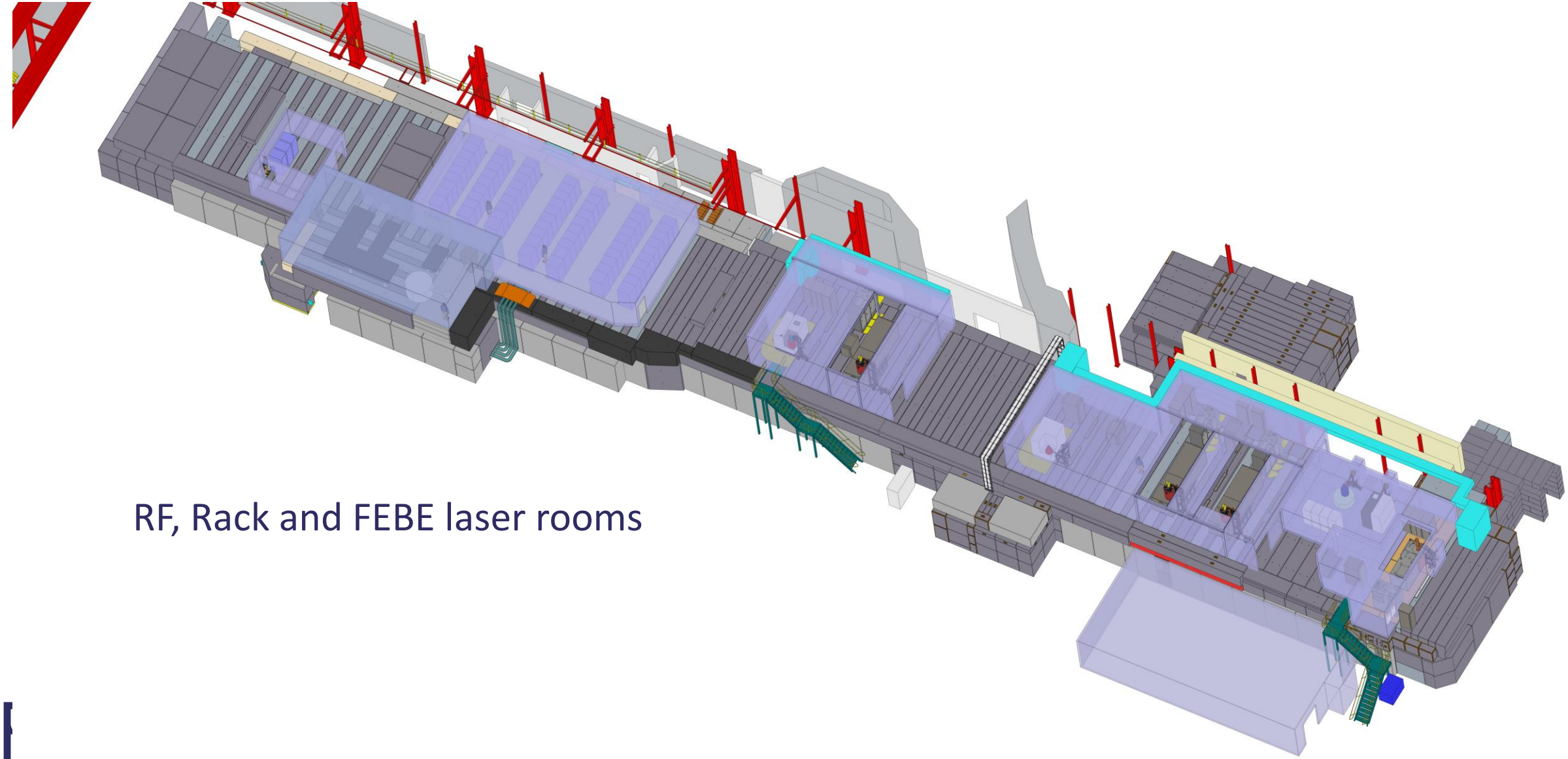
R&D: dedicated effort required beyond standard operations, and/or new diagnostics technology required.

CLARA 250 MeV - Accelerator Hall



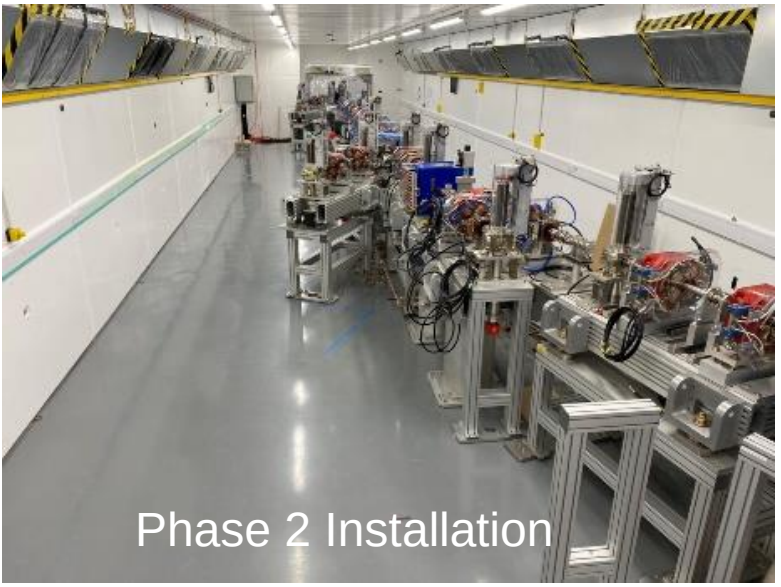
Status 2022

CLARA 250 MeV - Accelerator Hall Roof



RF, Rack and FEBE laser rooms

Phase 2 Preparation Progress


Phase 2 Installation

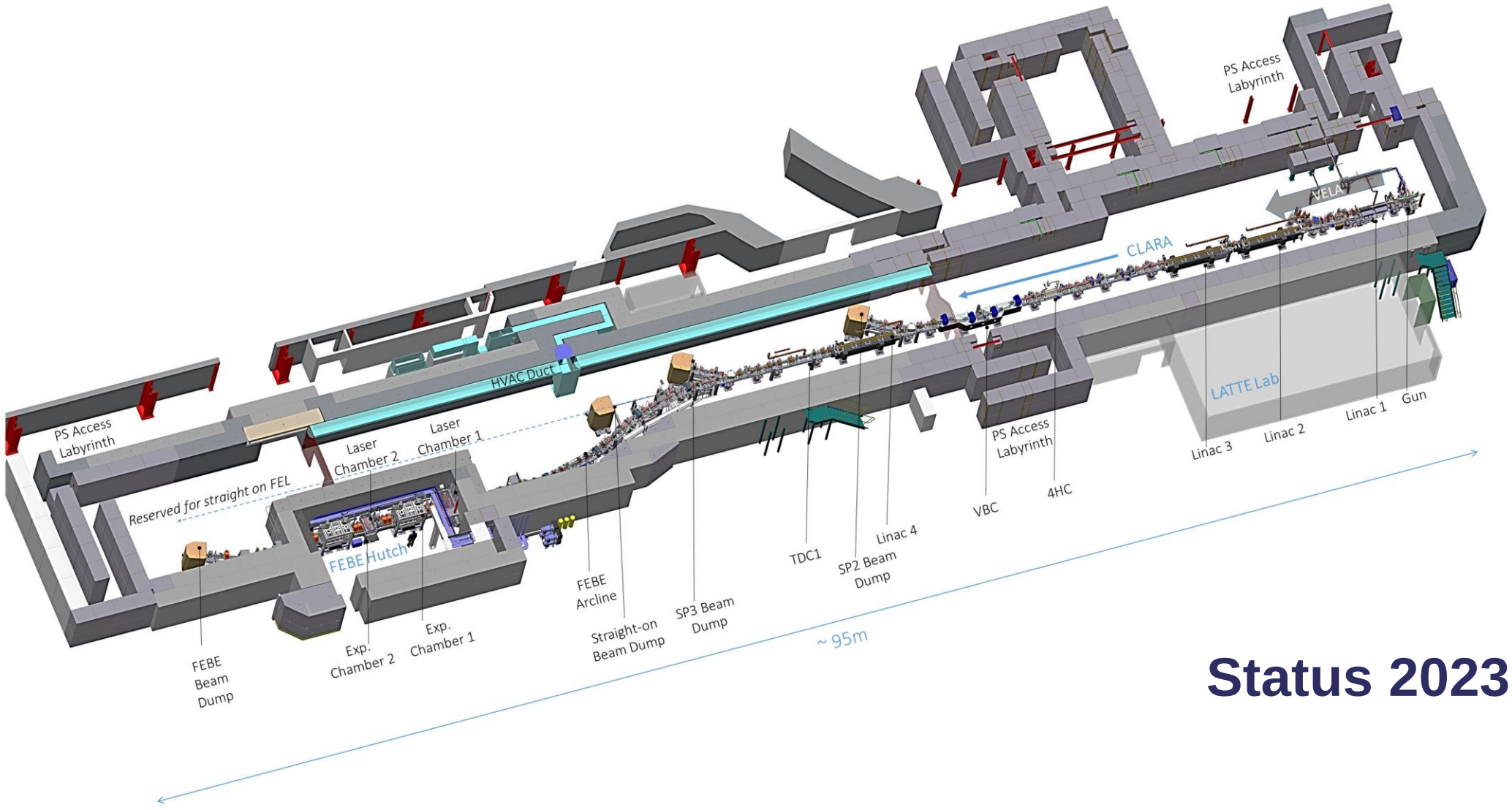

FEBE Hutch


FEBE Laser Room and
Rack Room 4 on Roof


RF Room 2
Linac 2 & 3 modulators

- Accelerator module construction & installation progressing as planned
- All modules built off-line in the Engg Technology Centre.
- Mechanical build, alignment, vacuum and electrical tests of all modules is complete
- Completion of 100TW Laser room complex
- Electrical/mechanical services installation
- Painting floors and bunker surfaces to allow clean installation

CLARA 250 MeV - Accelerator Hall



Status 2023

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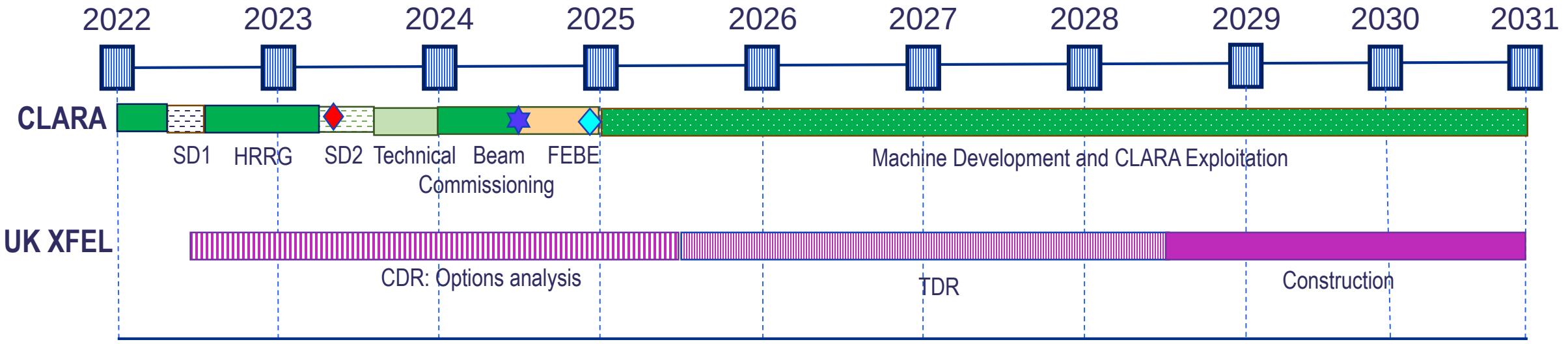
CLARA & UK XFEL Schedule



FEBE Laser contract begins

FEBE Exploitation kick off meeting

FEBE Laser ready for exploitation

SD1 Shutdown - Gun Modulator/klystron change

SD2 Shutdown - Phase 2 installation

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Summary

- CLARA FE has delivered high brightness beam for several novel applications successfully over two user runs from 2018 leading to many high impact publications.
- Upon completion of CLARA Phase 2 in 2024, 250 MeV FEL ready beam will be available to UK and international community.
- FEBE will offer a unique facility to users to work on a configurable, easily accessible (both regular calls and the hutch) high quality electron beam with femtosecond synchronised high energy laser light.
- 400 Hz gun conditioning/commissioning will start in August 2022 on the VELA line, which will allow us to swap this gun to CLARA line during Phase 2 shutdown (planned to start February 2023)
- Straight-on space (Phase 3) is retained for accelerator technology R&D in support of UK XFEL.

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Acknowledgments

Thanks to everyone in the CLARA team & CLARA Users.