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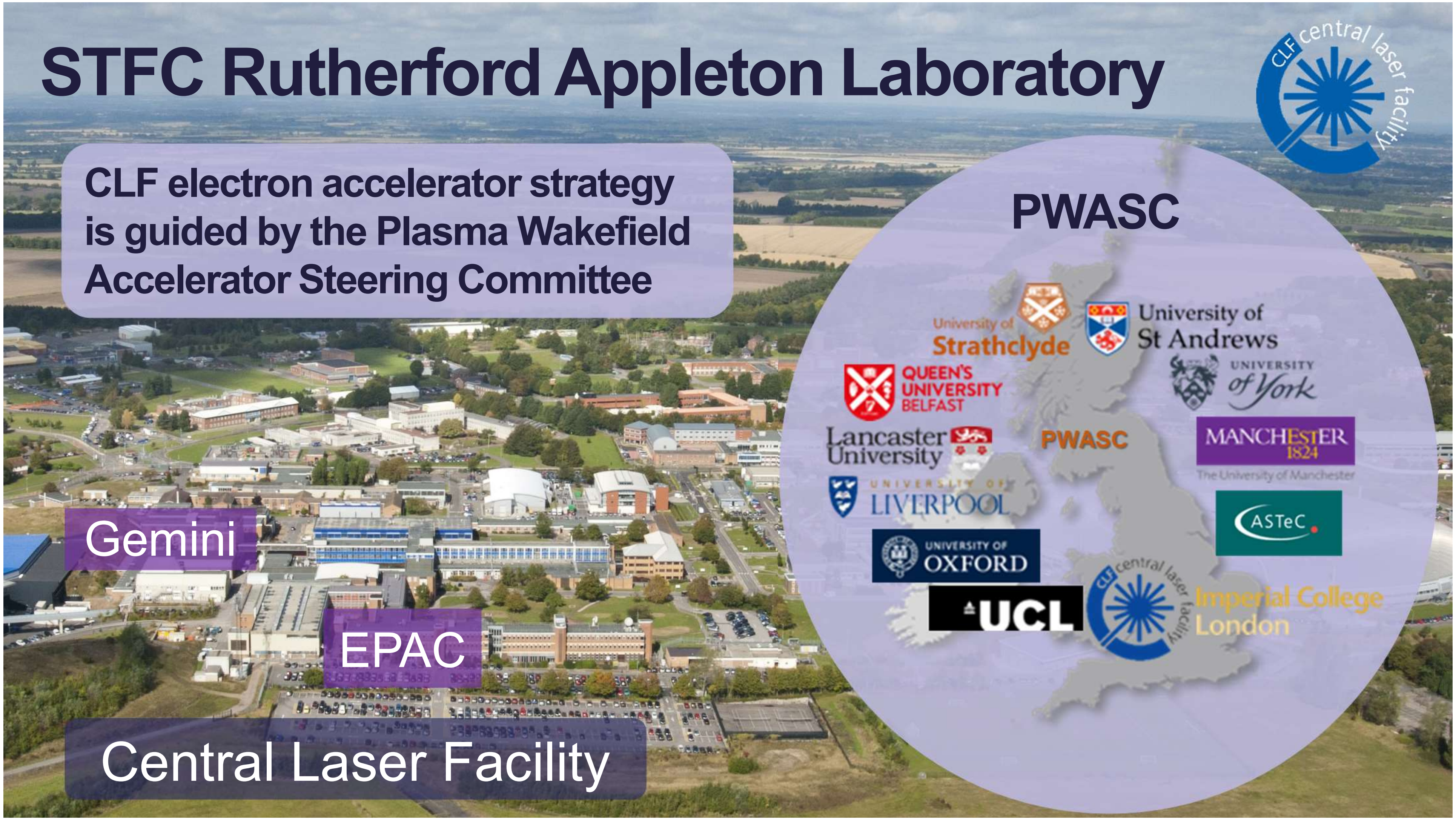
EPAC: A New, Advanced Facility for Applications of Laser-driven Accelerators

Daniel Symes
Central Laser Facility
Rutherford Appleton Laboratory

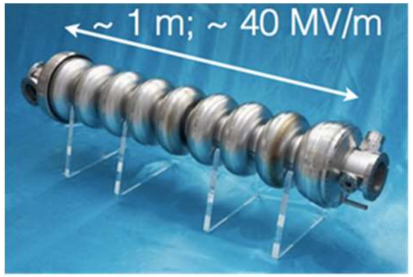
Particle Accelerators and Beams Conference 30 June 2023

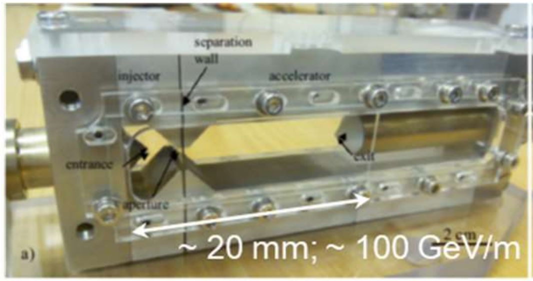

STFC Rutherford Appleton Laboratory
CLF electron accelerator strategy is guided by the Plasma Wakefield Accelerator Steering Committee
PWASC
University of Strathclyde
University of St Andrews
Queen's University Belfast
University of York
Lancaster University
PWASC
Manchester 1824
The University of Manchester
University of Liverpool
ASTeC
University of Oxford
UCL
Imperial College London
CLF central laser facility
Gemini
EPAC
Central Laser Facility

Compact laser-plasma accelerators

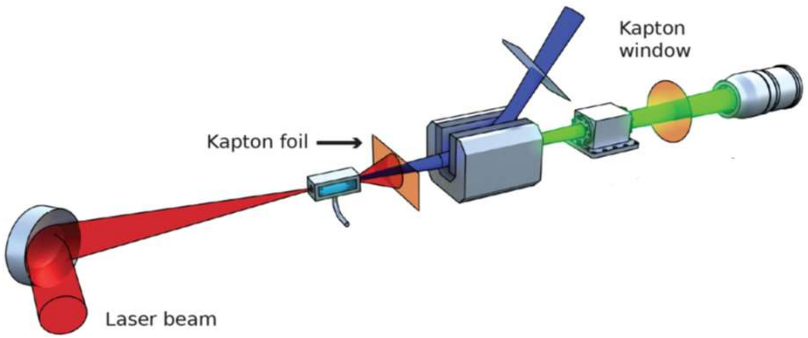
Laser wakefield acceleration

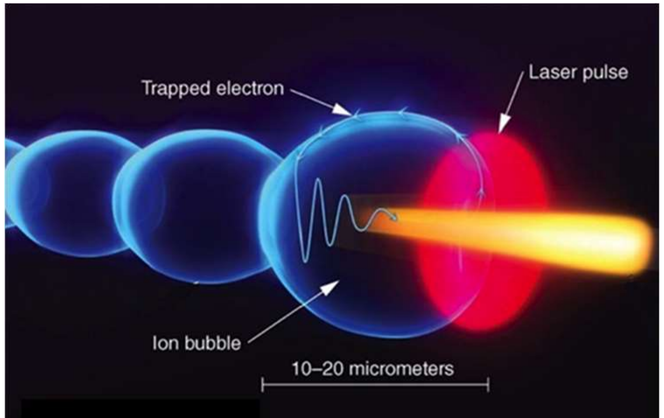
- cm-scale gas target
- Intense laser driver
- Multi-GeV electrons





Plasma supports extremely high accelerating fields (100 GeV/m)





Albert et al PPCF **56**, 084015 (2014)

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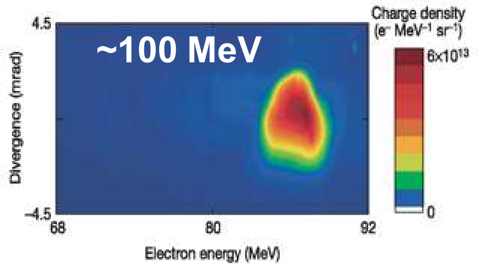
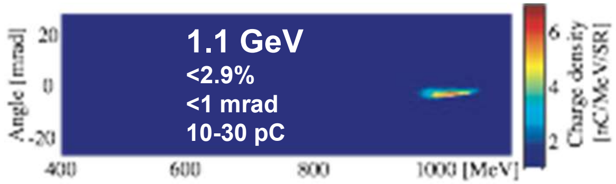
Progress in laser wakefield acceleration

10 TW laser, mm-scale plasma

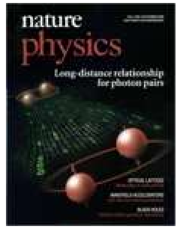


C. G. R. Geddes *et al.*, Nature,431, p538 (2004)
*S. Mangles *et al.*, Nature 431, p535 (2004)
*J. Faure *et al.*, Nature 431, p541 (2004)

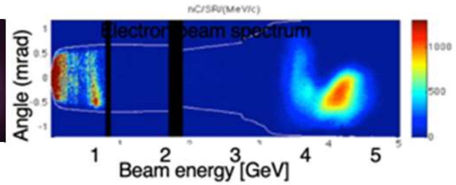
40 TW laser, cm-scale plasma



W.P. Leemans *et al.*, Nature Physics 2, p696 (2006)



310 TW laser, 9 cm-scale plasma



W.P. Leemans *et al.*, PRL 113, 245002 (2014)

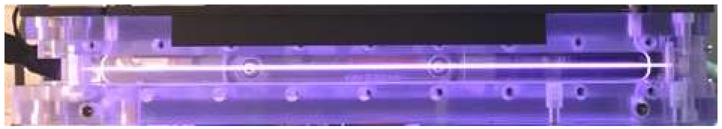
2004

2006

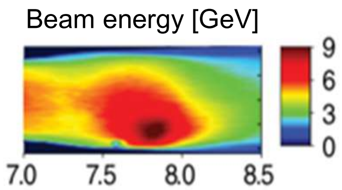
2014

2019

1 PW laser, 20 cm-scale plasma



Gonsalves *et al.*, PRL 2019



Challenges for laser-plasma accelerators

R & D is needed to produce consistent, high quality LWFA beams for light-sources and high-energy physics applications

The European Strategy for Particle Physics **Accelerator Roadmap** highlights research priorities for plasma acceleration

Key beam properties are:

- Beam stability & quality
- Luminosity, energy, efficiency

Goal is to produce a plasma-based collider in ~ 30 years

CERN-2022-001

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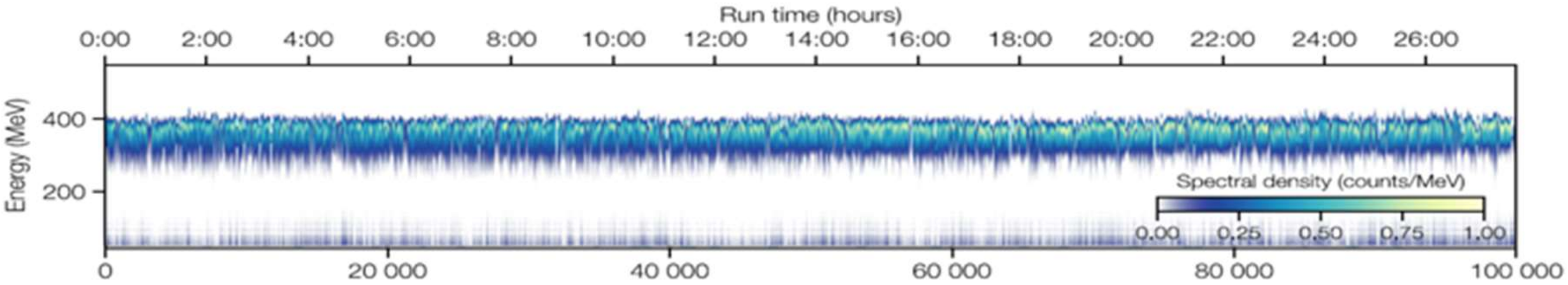
Plasma accelerator performance has improved dramatically in recent years



Electron beam energy over 24 hours
Maier et al PRX **10**, 031039 (2020)

Stable accelerator operation has been shown over extended periods

- Commercialisation of laser technology
- Industrial approach to source development

System can be stabilised with active feedback

- Remove fluctuations caused by laser, environment, and target
- Scale up to multi-GeV, 10 Hz operation

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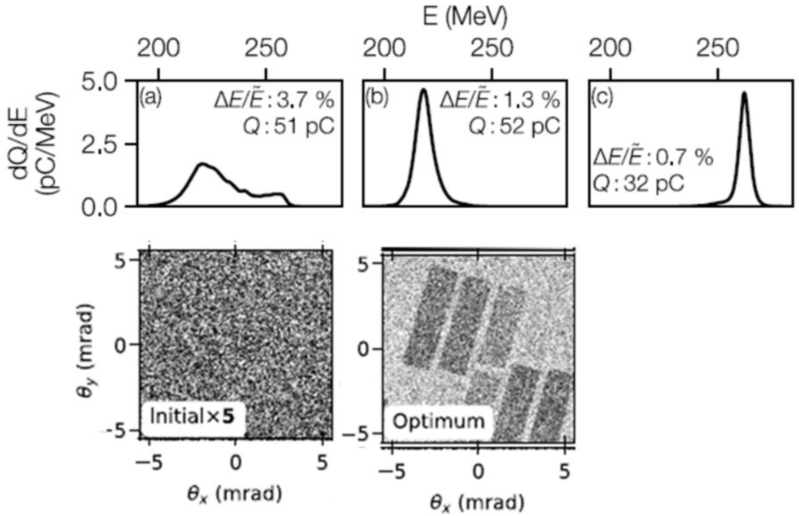
Accelerator can be optimised using machine-learning techniques

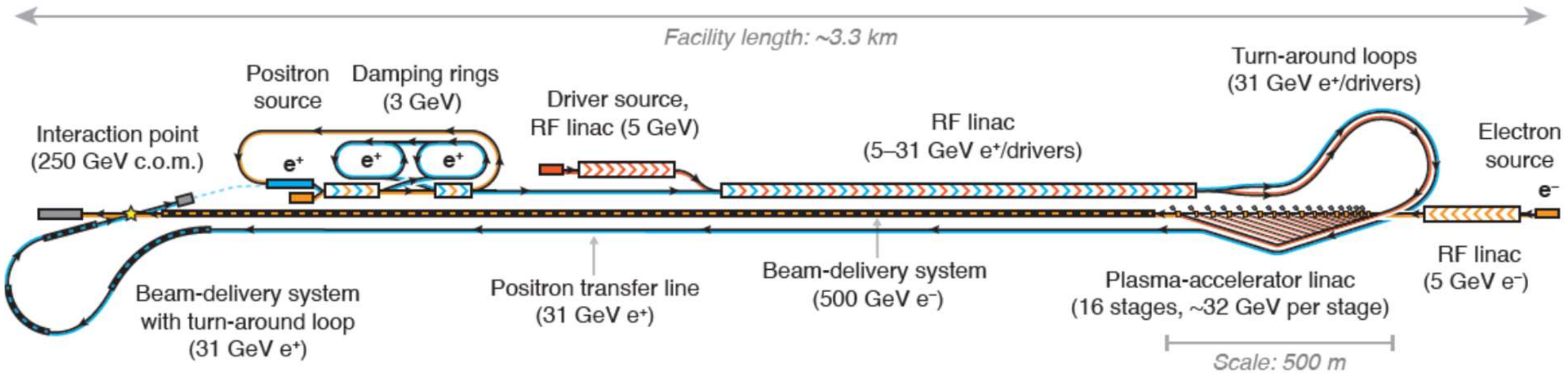
Bayesian Optimisation

- Optimise specific properties by varying laser pulse shape and target parameters in a feedback routine
- Aim to achieve all required beam properties simultaneously – high energy, low spread, low emittance
- Produce stable, tuneable electron and x-ray beams



Bayesian optimisation of LWFA
Shalloo et al Nature Comm. **11**, 6355 (2020);
Jalas et al PRL **126**, 104801 (2021)

Collider concept using hybrid technology

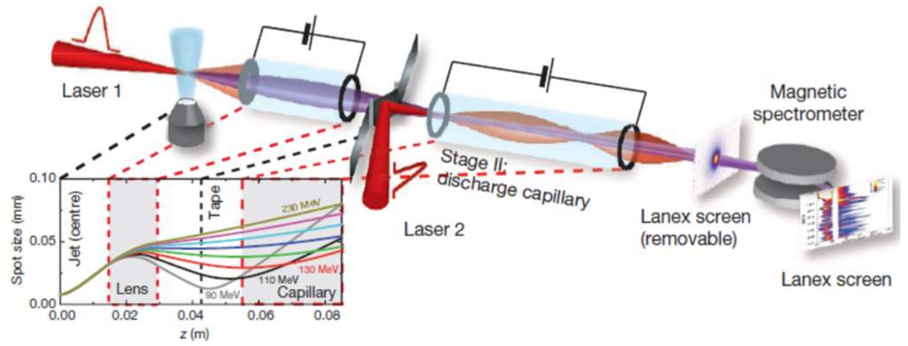


Hybrid asymmetric linear Higgs Factory
Foster et al arxiv.org/pdf/2303.10150.pdf

Two-stage LWFA at LBNL
Steinke et al Nature **530**, 190 (2016)

High luminosity: laser driver repetition rates beyond kHz with high wall-plug efficiency

High energy: Staging multiple modules to reach 100s GeV energies



Extreme Photonics Applications Centre

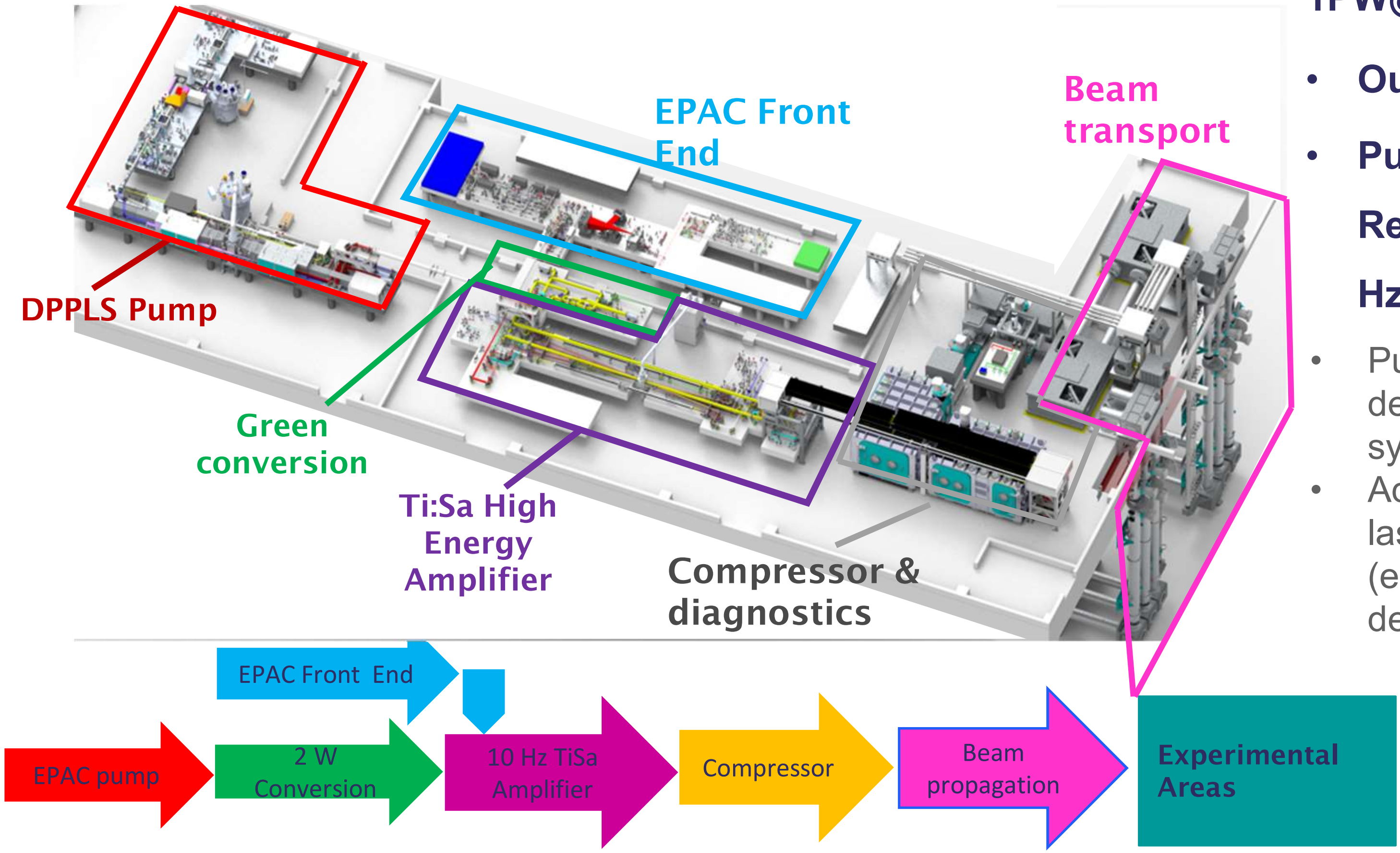
- £100M investment (UKRI & MOD)
- ~ £6M p.a. expected operational cost
- Installation underway
- Operational in 2026

clf.stfc.ac.uk/Pages/EPAC-introduction-page.aspx

EPAC will be a driver for fundamental science and LPA applications

- State-of-the-art 10 Hz, 1 PW laser with two independent experimental areas
- Major upgrade to UK infrastructure for academic high-power laser community
- Focus on developing 10 Hz plasma accelerators for a range of applications in industry, medicine, defence, and security
- Improved capability for studies of fundamental science using laser-driven secondary sources

EPAC Laser System



EPAC specification

1PW@10Hz

- **Output Energy 30 J**
- **Pulse duration ≤ 30 fs**

  Repetition rate 10 Hz, 1 Hz, Shot on Demand
- Pump for Ti:S is CLF developed 100J DiPOLE system.
- Additional space for future laser and experimental areas (eg. a 100Hz system under development)

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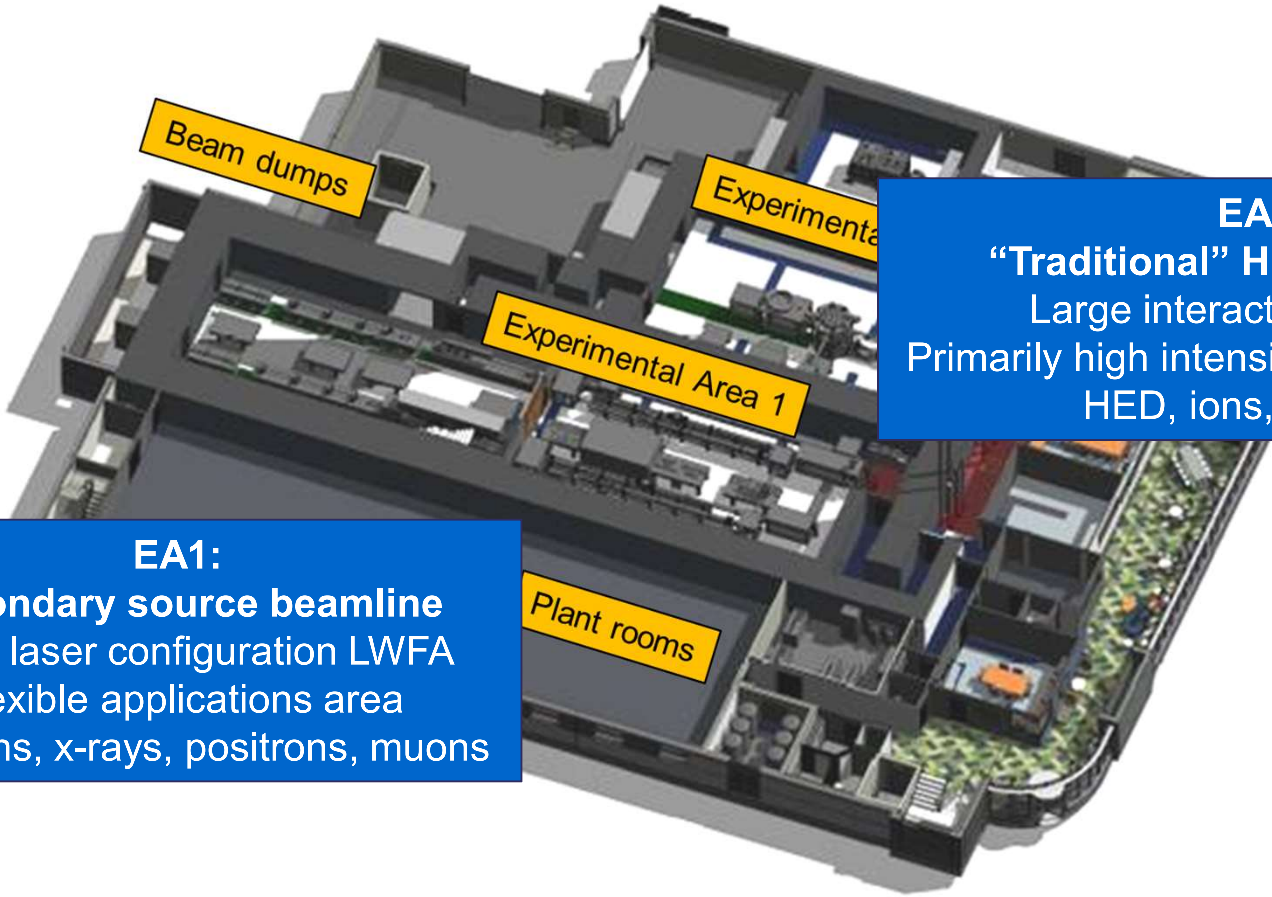
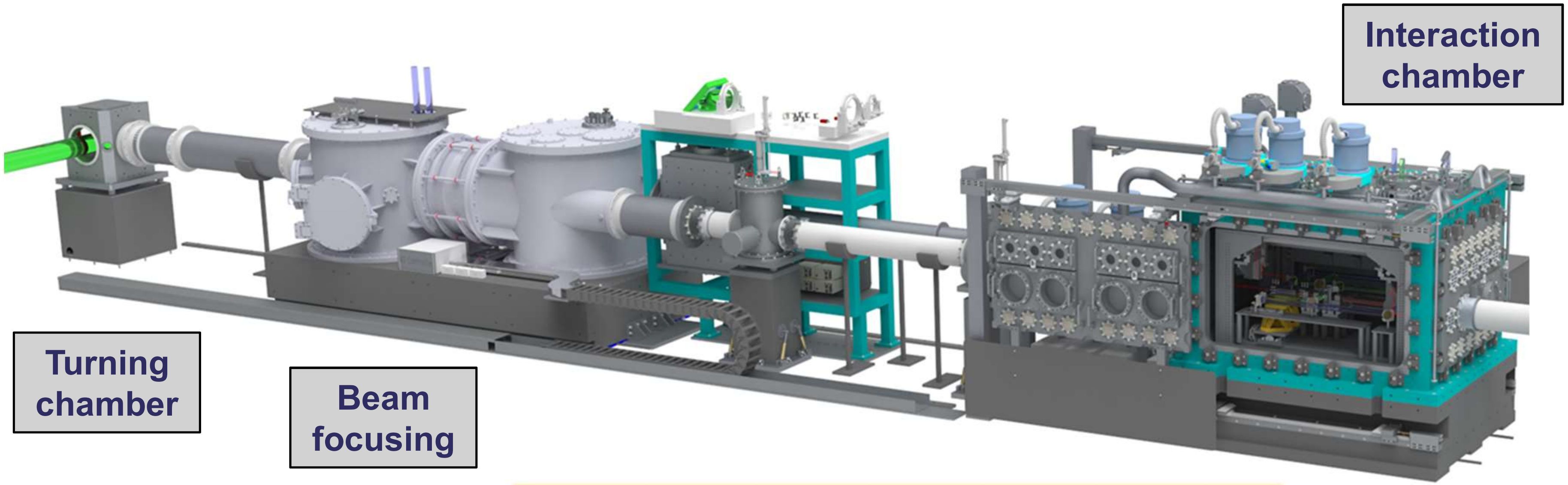
Shielded target areas on the ground floor



EA2:
"Traditional" HPL target area
Large interaction chamber
Primarily high intensity solid interactions
HED, ions, neutrons

EA1:
Secondary source beamline
Fixed laser configuration LWFA
Flexible applications area
Electrons, x-rays, positrons, muons

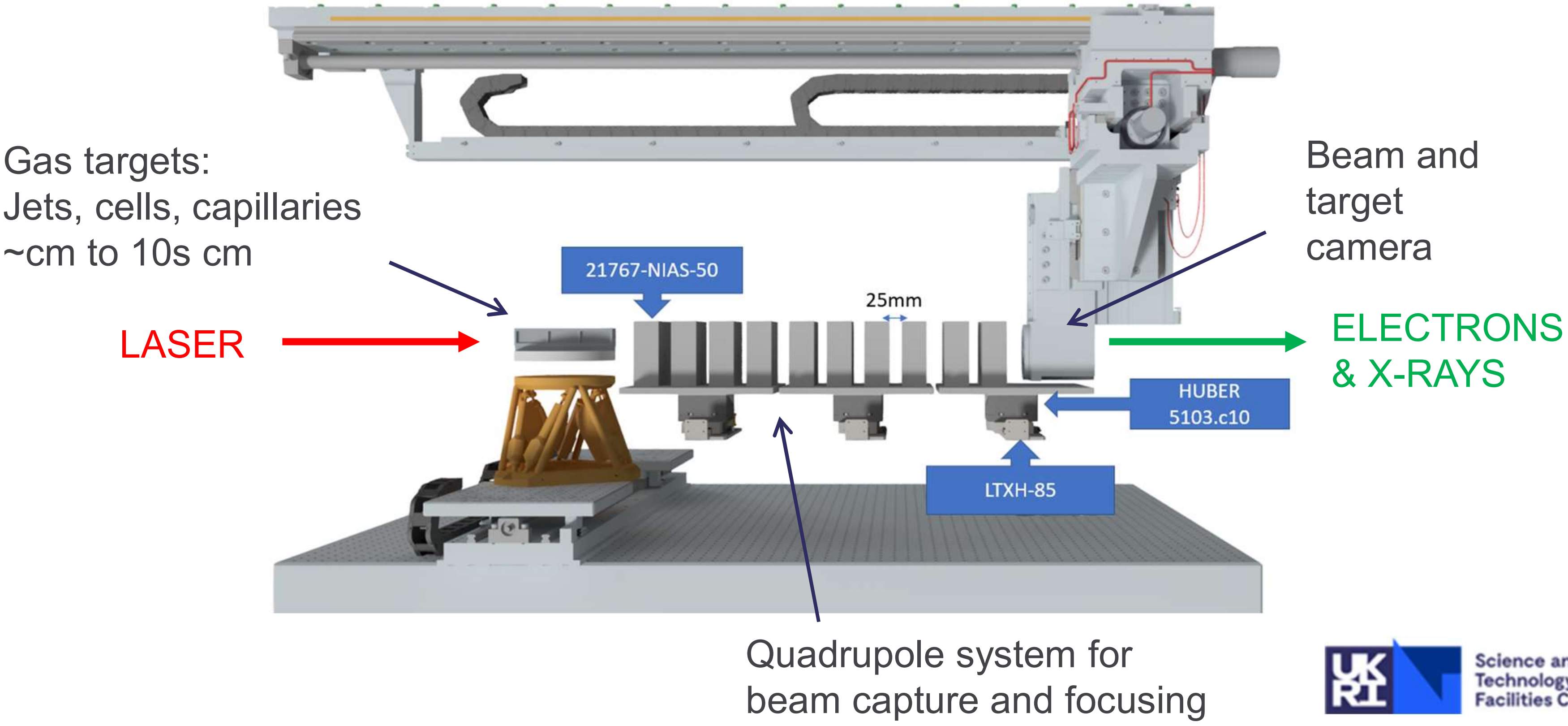
Experimental Area 1 houses a PW-driven laser wakefield electron accelerator



14 m OAP for 30 J
Focused to relativistic intensity ~ 6 x 10^{18} Wcm^{-2}

Timeline:
2023: Chambers and large equipment delivered
2024: Commissioning with internal laser
2025: Pulsed beam and LWFA commissioning
2026: Operational user facility

Interaction chamber houses LWFA, diagnostics, and quadrupole magnets



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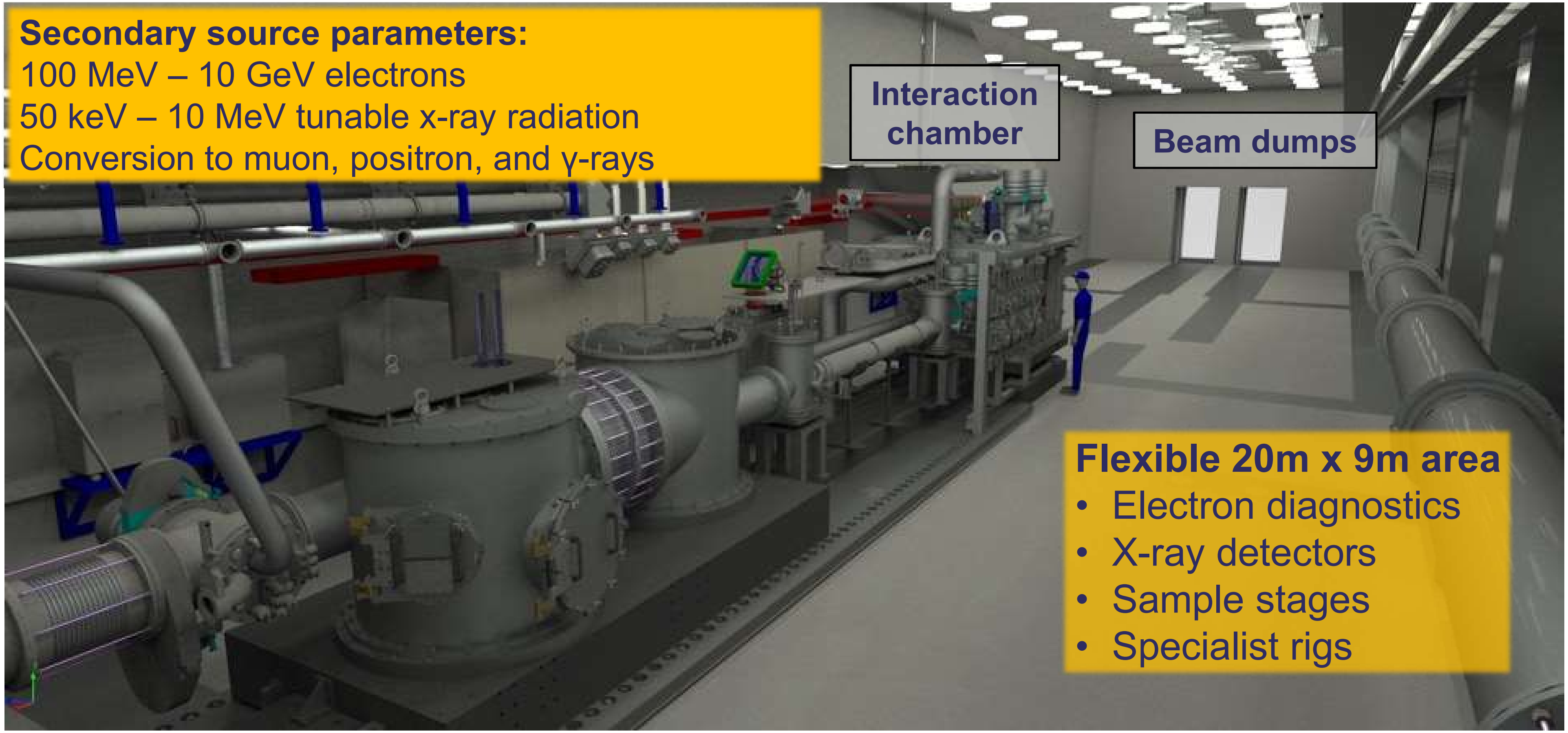
EA1 Application area

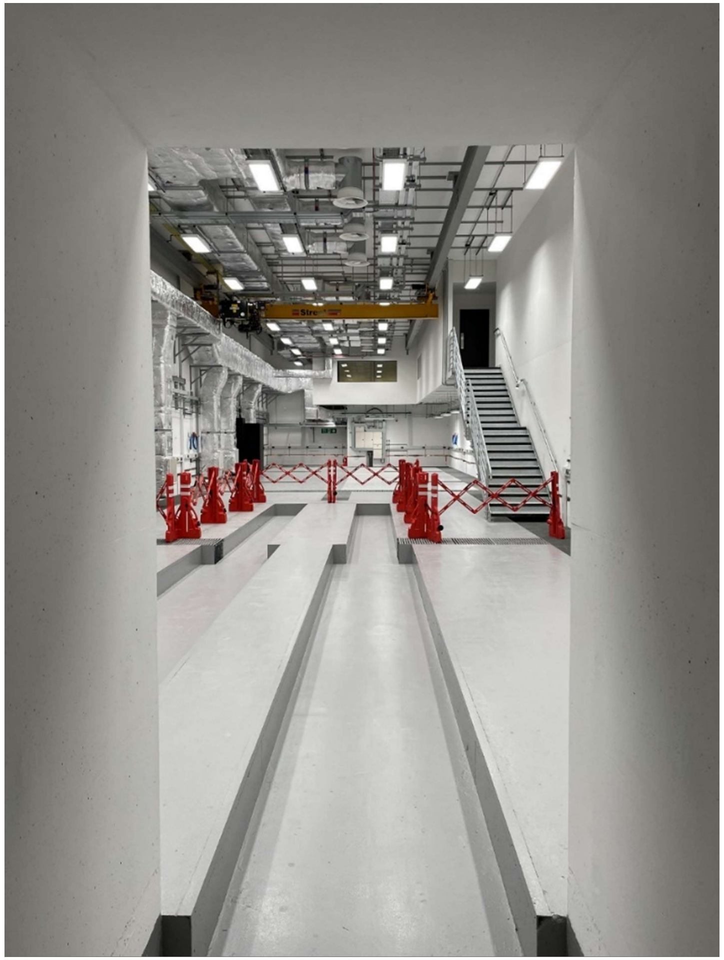
Secondary source parameters:
100 MeV – 10 GeV electrons
50 keV – 10 MeV tunable x-ray radiation
Conversion to muon, positron, and γ-rays



Flexible 20m x 9m area

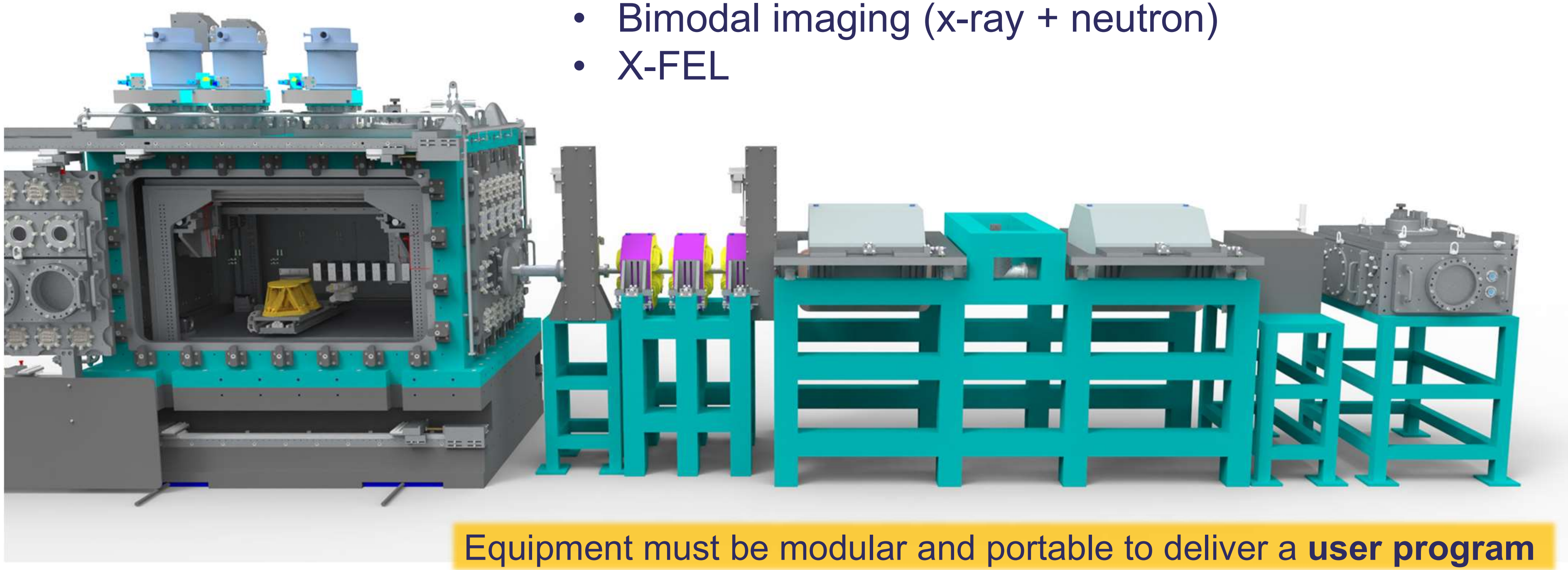
- Electron diagnostics
- X-ray detectors
- Sample stages
- Specialist rigs

EA1 internal view



EA1 beamline requirements

- Impact (positrons / muons / bremsstrahlung)
- Collisions (Inverse Compton Scattering & QED)
- X-ray Diffraction and Spectroscopy
- Bimodal imaging (x-ray + neutron)
- X-FEL



Equipment must be modular and portable to deliver a **user program**

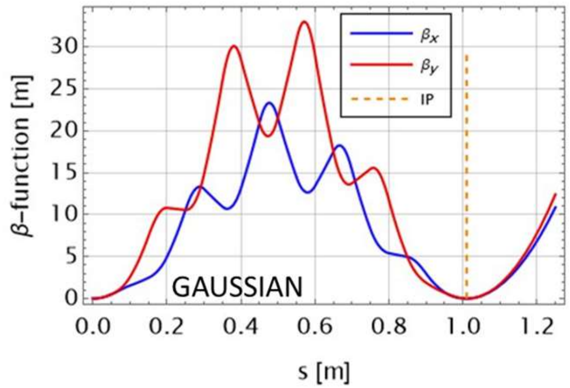
Start-to-end simulations

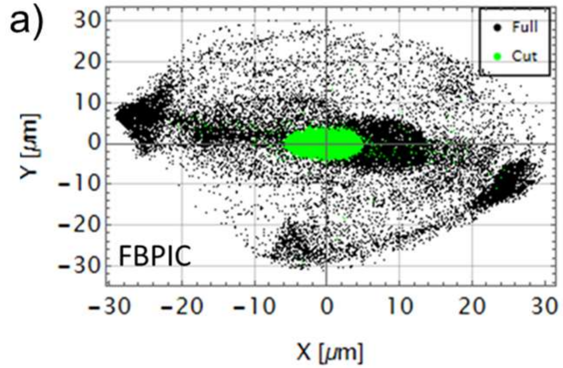
- **Start-to-end** simulations – PIC for LWFA + magnet tracking codes
- Gaussian beams are **not** representative because of LWFA energy spread

Difficulties:

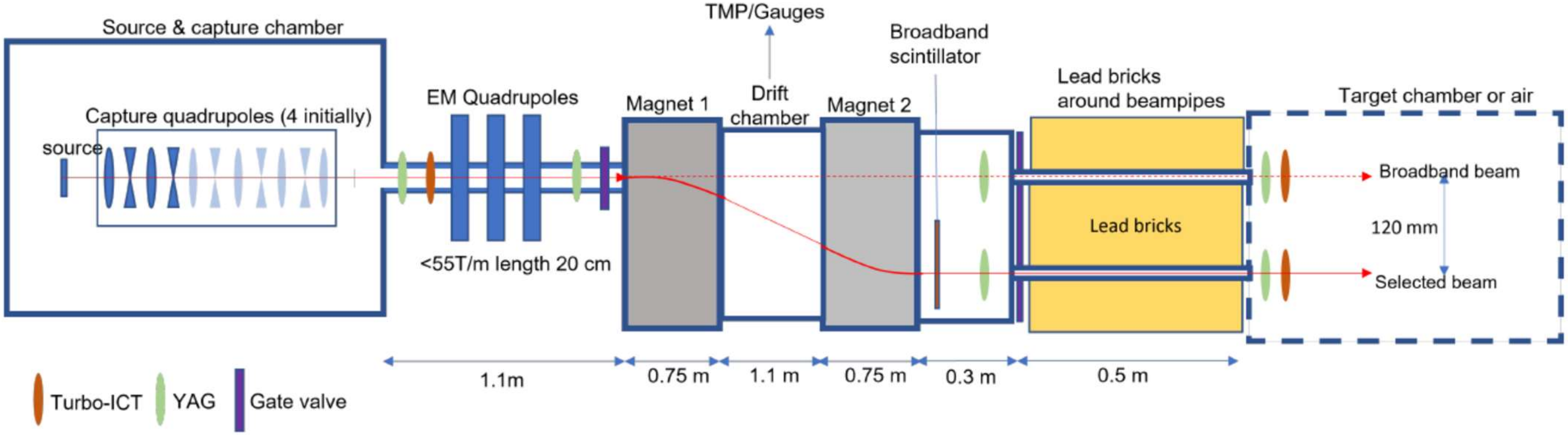
- Converting PIC output into useable input to tracking codes
- **High energy** – most LWFA beamline designs have been at 100s MeV level
- **Detail** – most published work does not fully analyse the system
- **Flexibility** – EPAC is driven by user demands, it needs to offer a choice of energy and sample position

The wide range of science demanded by EPAC means we need **multiple** beamline designs



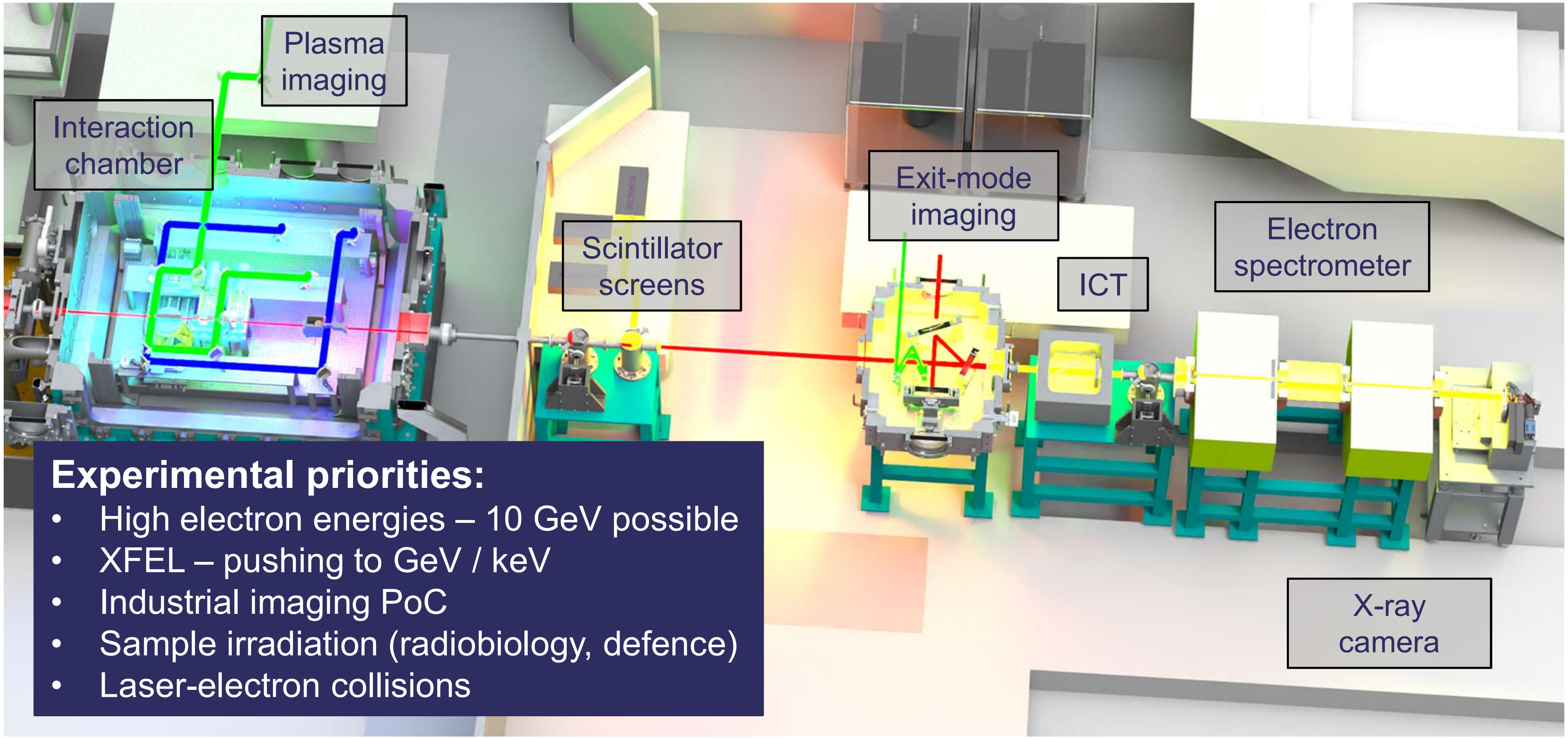


Electron focusing for 1 GeV beam



The first set of 4 PMQs control the divergence but do not form a focus.
Use the EM quad triplet to form focus at the required distance:
Diagnostics – spectrometer screen, transition radiation / emittance
Sample irradiation – high charge, broad band focussed metres from e-spec exit

EA1 beamline layout



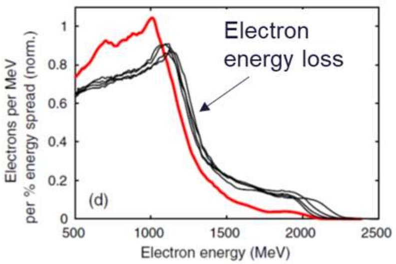
Experimental priorities:

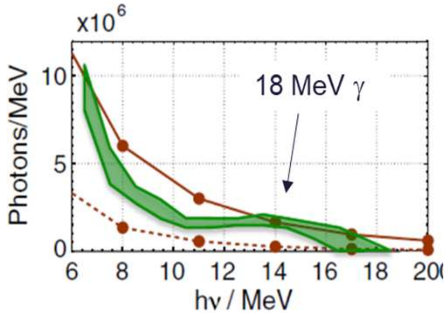
- High electron energies – 10 GeV possible
- XFEL – pushing to GeV / keV
- Industrial imaging PoC
- Sample irradiation (radiobiology, defence)
- Laser-electron collisions

Fundamental science using LWFA beams

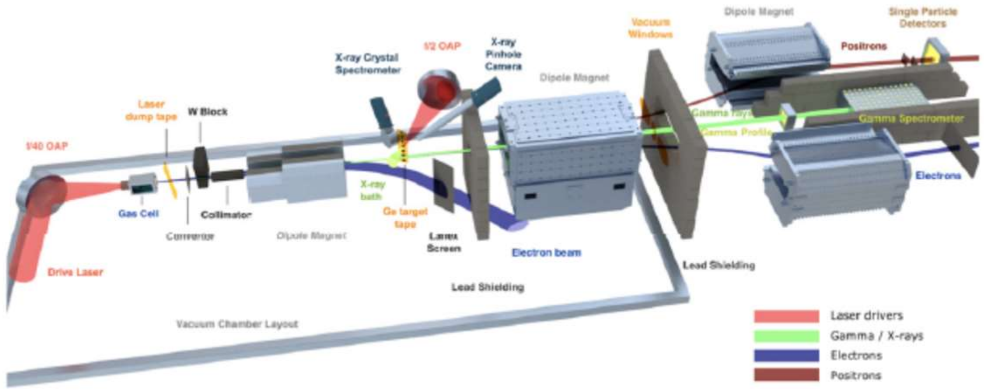
Pioneering dual beam experiments with the Gemini laser

- Multi-GeV e- colliding with 10^{21} Wcm^{-2} laser focus
- Measurable QED effects: radiation reaction, pair production, γ-γ scattering
- Non-linear Inverse Compton Scattering





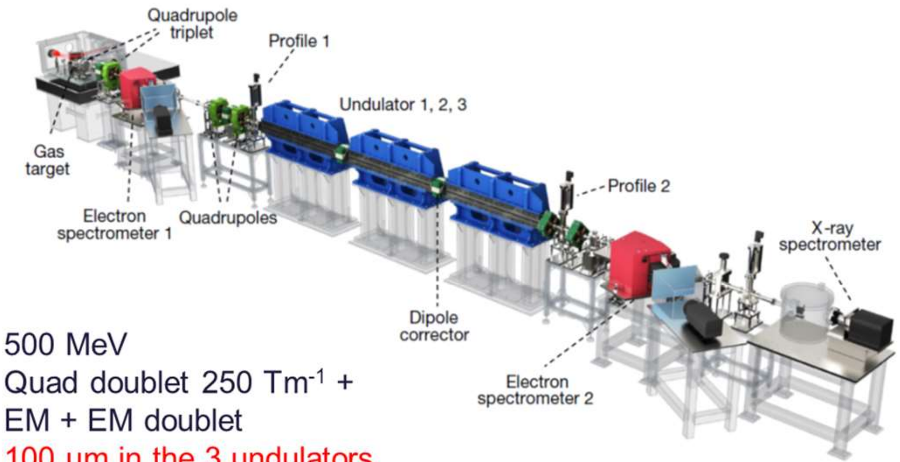
Radiation reaction and non-linear ICS
Cole 2018, PRX **8**, 011020; Poder 2018 PRX **8**, 031004; Sarri 2014 PRL **113**, 224801



Beamline arrangement for dual beam experiments
Kettle 2021, NJP **23**, 115006

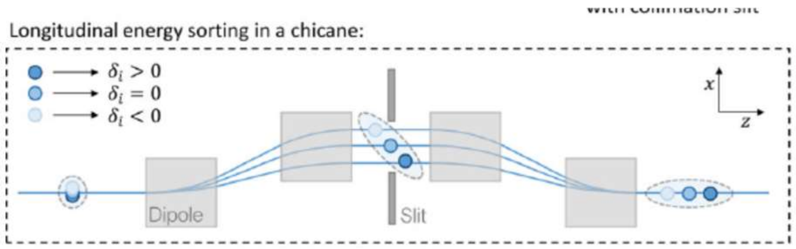
EPAC will have much better stability & higher repetition-rate

LWFA driven Free-Electron-Laser

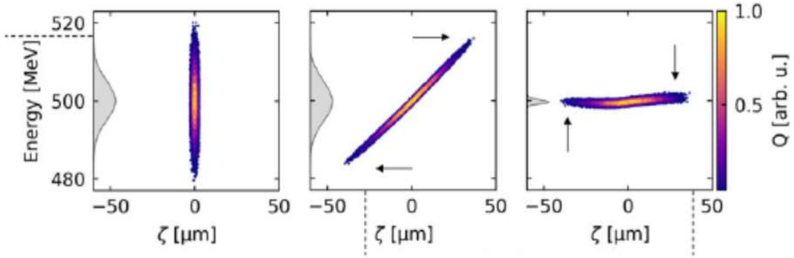


- 500 MeV
- Quad doublet 250 Tm^{-1} + EM + EM doublet
- 100 µm in the 3 undulators

LWFA-driven FEL: Wang 2021, Nature **595**, 516



Decompress/dechirp scheme: Pousa 2022 PRL **129**, 094801



LWFA and compact undulators can shrink size and cost but significant R&D is required

- 3 significant results in Nature recently (SIOM, INFN and HZDR)
- DESY have proposed conditioning scheme to reduce LWFA energy spread to 0.1%

EPAC aims to increase electron energies to GeV and x-ray range to keV

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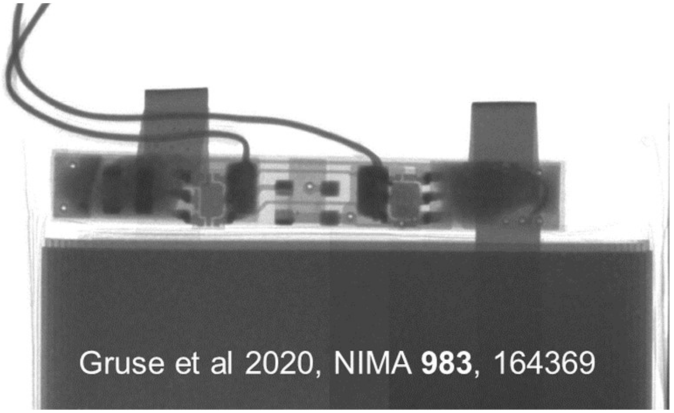
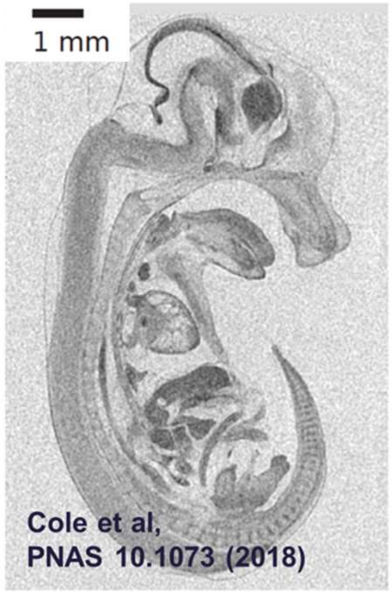
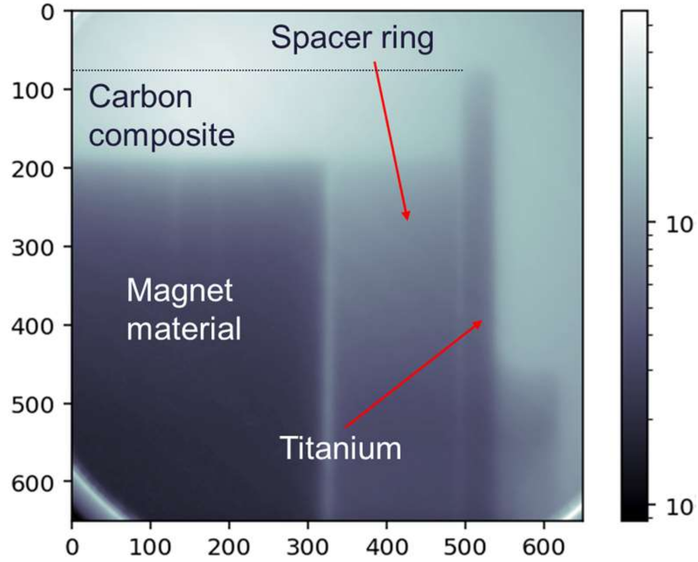
Imaging using LWFA x-ray sources



Radiography and µCT at 20 keV, 30 µm resolution



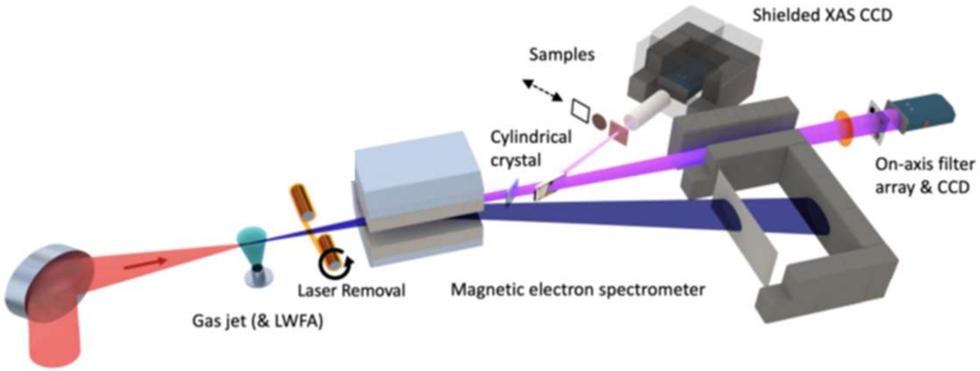


Radiography with MeV brems. ~400 µm resolution

EPAC will produce a range of x-ray energies suitable for **dynamic imaging** of composite, polymer, metallic, and dense objects

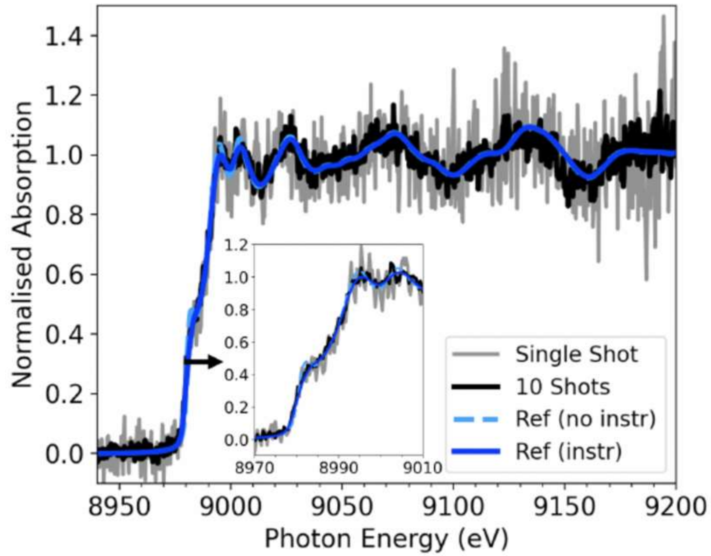
Rolls-Royce UKRI Science and Technology Facilities Council

Ultrafast XAS measurements with betatron



- **Pump-probe with 10s fs temporal resolution – competitive with XFELs**
- Studies of ultrafast transitions in HED plasmas
- Industrial product development – materials, batteries, photovoltaics

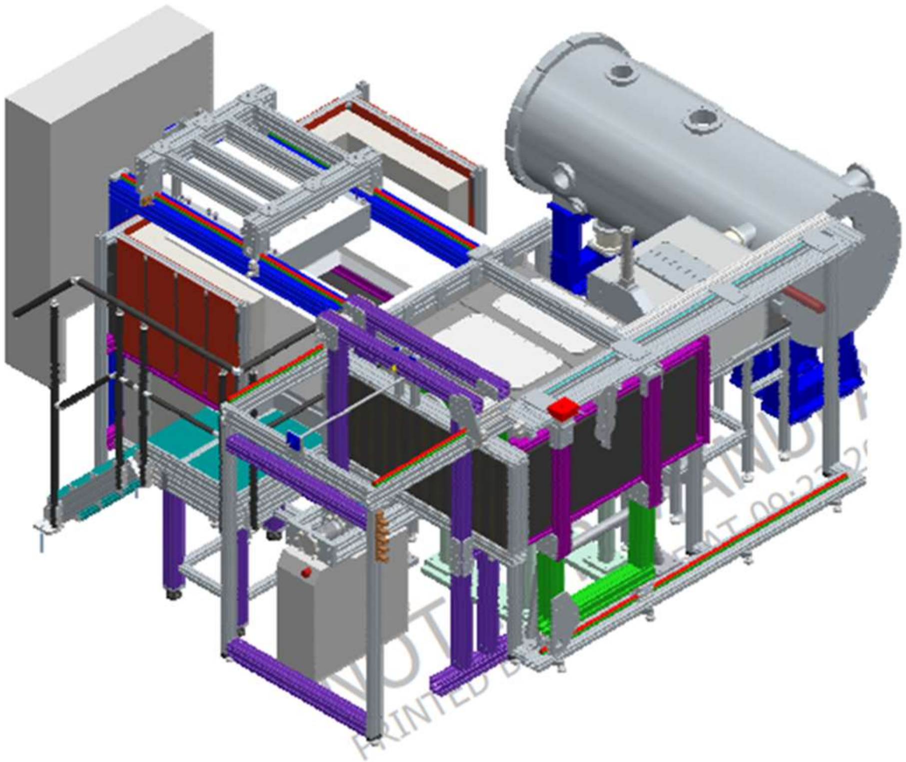
EPAC will increase the quality and acquisition rate of XAS data



Single-shot XANES and EXAFS of Cu edge
Kettle 2019, PRL 123, 254801;
Kettle 2023 arxiv.org/pdf/2305.10123.pdf

Johnson Matthey Inspiring science, enhancing life
John Adams Institute for Accelerator Science
Imperial College London
UKRI Science and Technology Facilities Council

LWFA preparation for EPAC



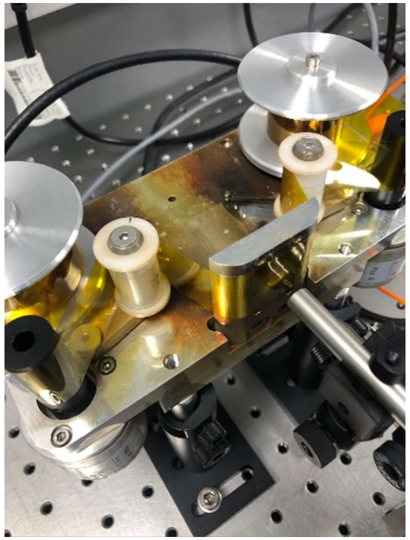
Produce stable 5 Hz 100 MeV e- beams

- Investigate laser stability
- Implement stabilisation systems
- Implement Bayesian optimisation code
- Optimise LPA-driven x-ray sources

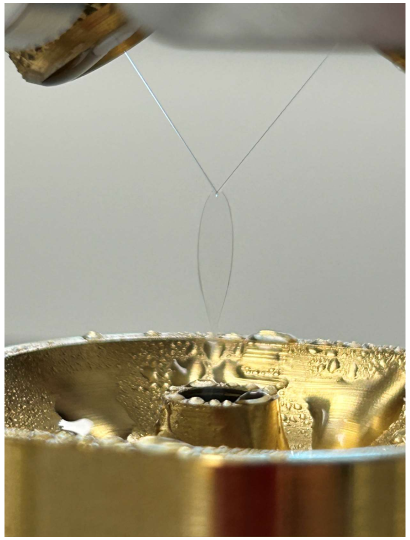
Automation and control of laser wakefield accelerators using Bayesian optimization
RJ Shalloo et al. Nat. Comm. **11**, 6355 (2020)

High rep-rate targetry

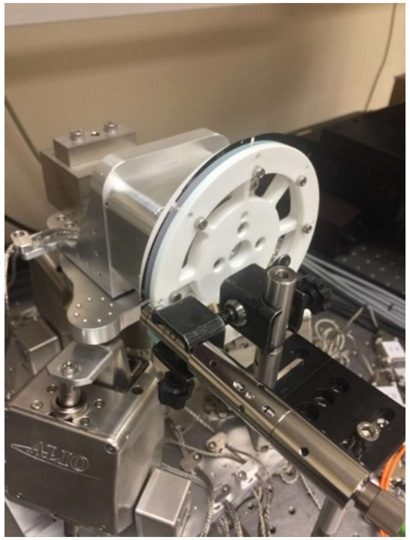
To meet the increasing rep rate there is a change in focus from single component manufacture and machining to batch and high rep rate production. Collaborations and developments internally and externally are helping us to meet this challenge

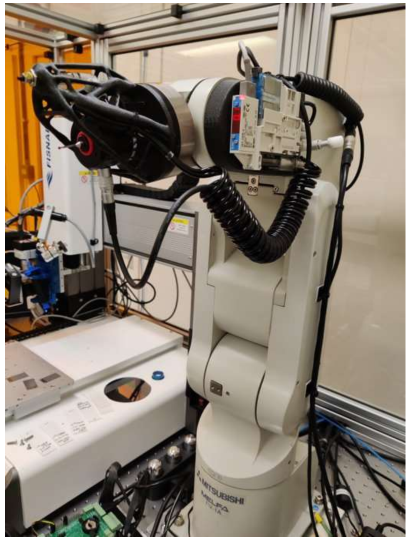


Tape targets with a 2μm position stability



Liquid sheets for plasma mirrors and targets





MEMS fabrication for mass-produced complex targetry

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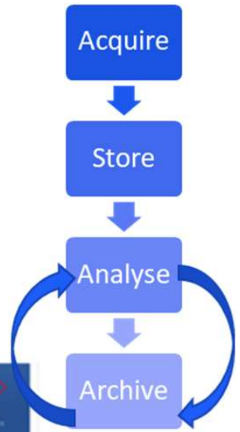
Data acquisition and management

10Hz operation introduces novel issues for laser-plasma diagnostics

- Afterglow / radiation hardness of scintillators
- Resolution / sensitivity to fully benefit from micron source size
- Flexibility to deal with unknown source performance

EPAC will record many diagnostics at high repetition-rate

- Up to 5 GB/s; 1 – 2 PB annually
- Data held centrally and accessed through STFC cloud
- Data analysis packages under development with remote access
- A new regime for high-power lasers but have expertise within STFC



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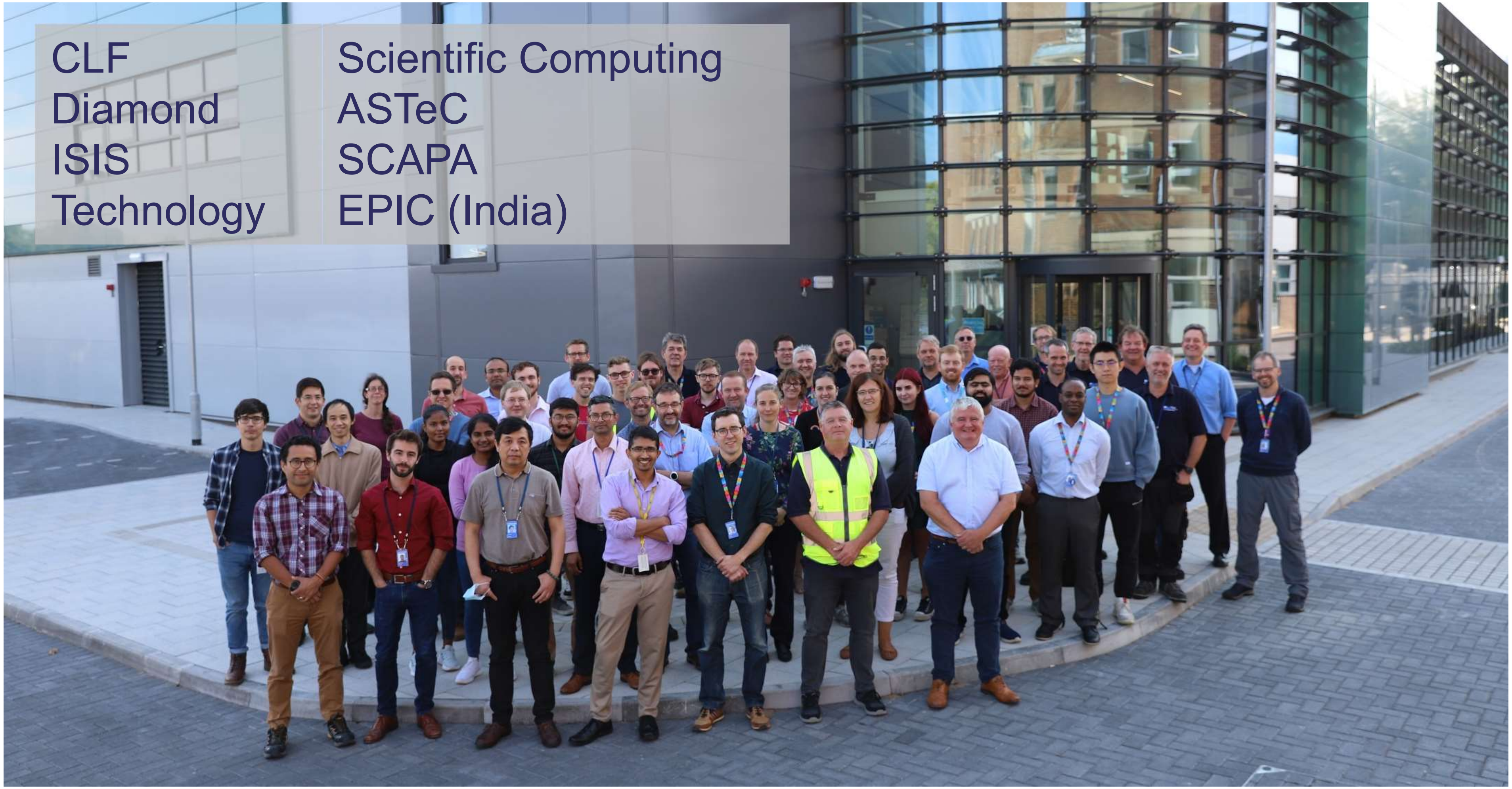
A large (international) collaboration is involved in building EPAC



EuPRAXIA @ EPAC – Potential upgrade path

A flagship international research facility for propelling laser-driven plasma accelerators to transformative real-world applications

EuPRAXIA will drive plasma accelerators producing 10 GeV electron beams at 100 Hz:
- Sources with unprecedented properties for industrial and medical applications
- Laser driven XFEL

EuPRAXIA will be located at two sites:
- Beam-driven based at INFN, Frascati
- Laser-driven to be decided – EPAC is one of four short-listed sites
- EPAC building could be extended for EuPRAXIA Experimental Areas

Preparatory phase (Nov 22 – Oct 26) is funded (3.5 M€)
- Choose second site (by 2024)
- Develop pre-TDR
- Project cost estimated 600 M€

EuPRAXIA is now on the ESFRI Roadmap for European Infrastructures

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Summary
Laser-driven accelerators are maturing

- LWFA has produced multi-GeV beams with reasonably low emittance, low energy spread, and high brightness but not simultaneously and continuously

- Producing high-quality beams from LWFA is central to proving their suitability for future large-scale facilities (eg. FELs, colliders…)

EPAC hopes to provide some milestones along the way, along with exploiting their applications

Experimental Area 2 overview

Flexible configurations to enable a wide range of experiments

- Primary focus on high density laser-matter interactions for:
  - Optimization of secondary sources
  - Fundamental science
- Range of focal lengths to explore different regimes for ion acceleration
- Long focus can provide x-ray backlighter for HED and WDM plasma
- Future second beamline to combine multiple radiation sources

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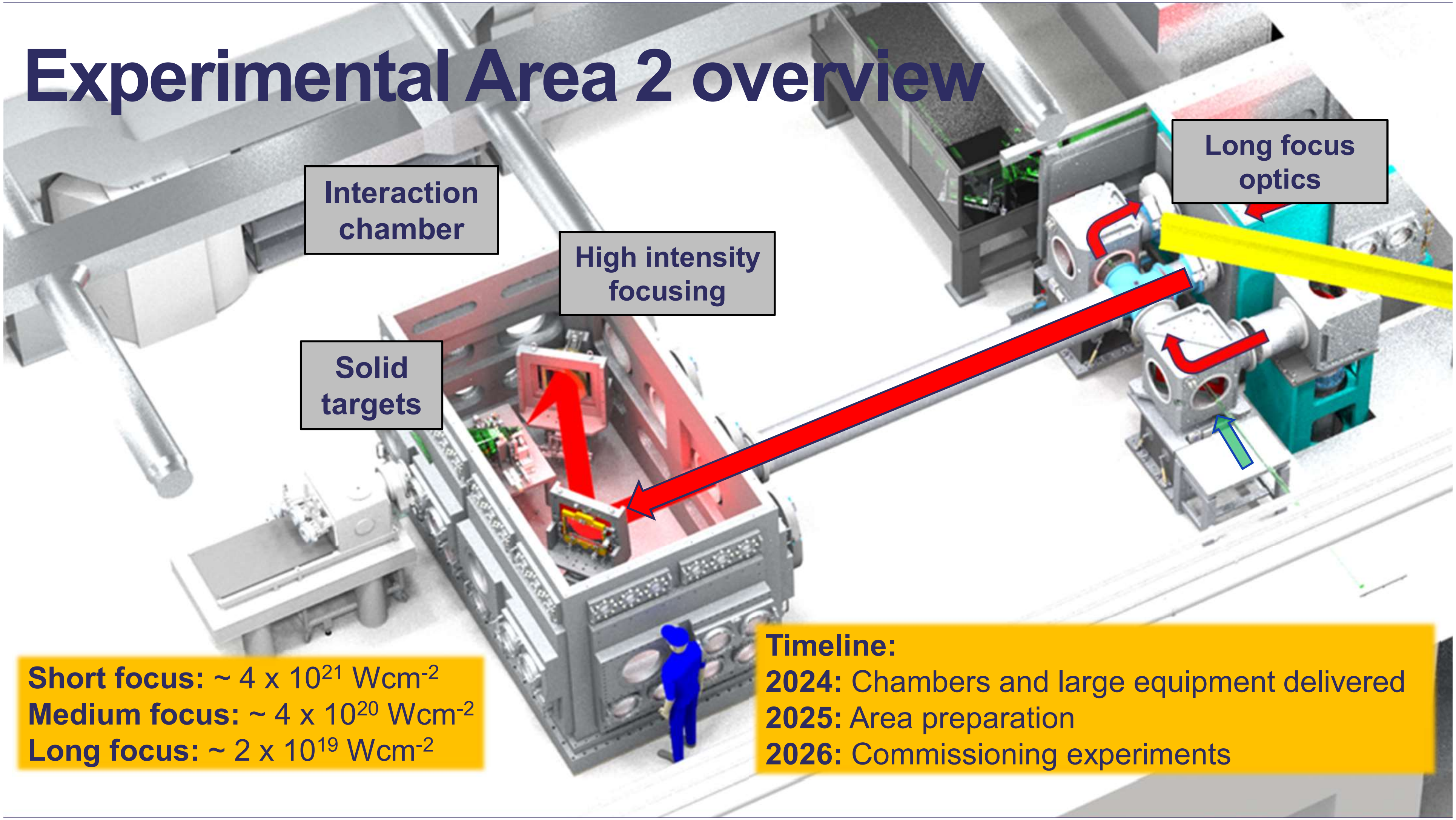
Experimental Area 2 overview



EA2 internal view