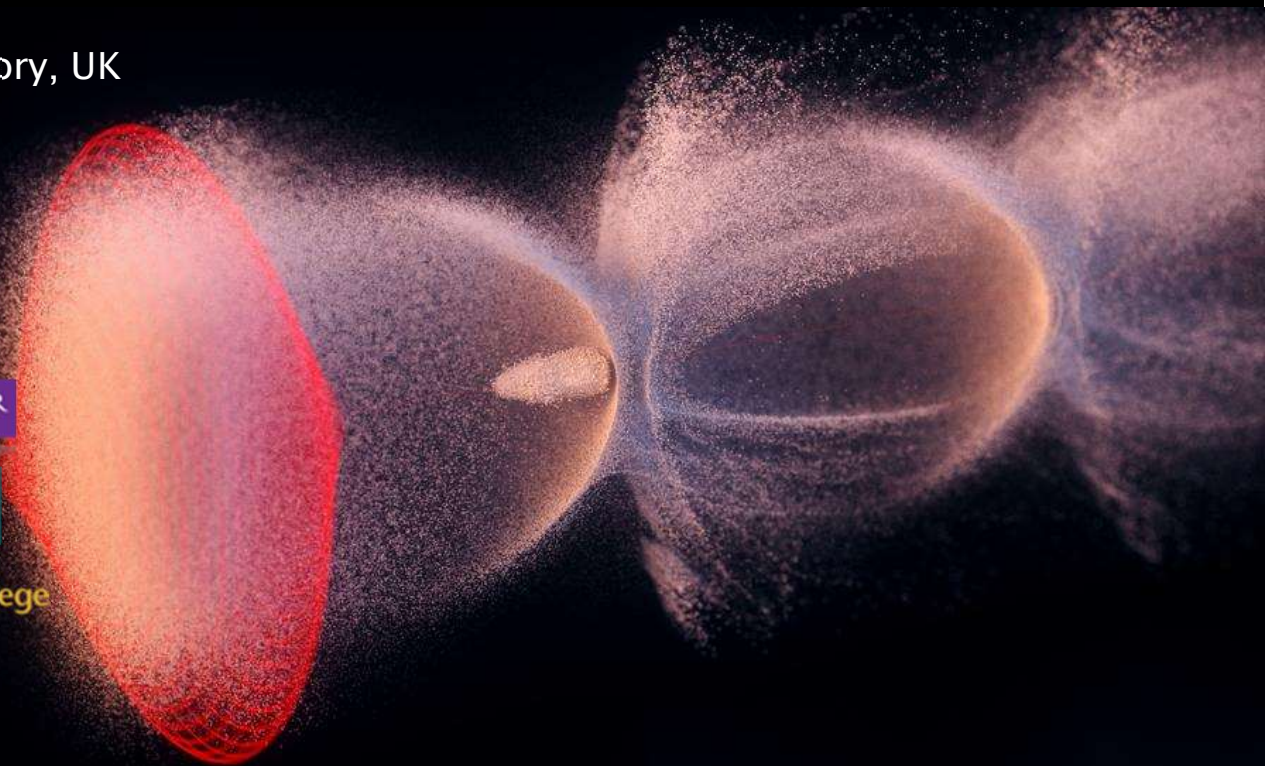


# Plasma Acceleration at EPAC

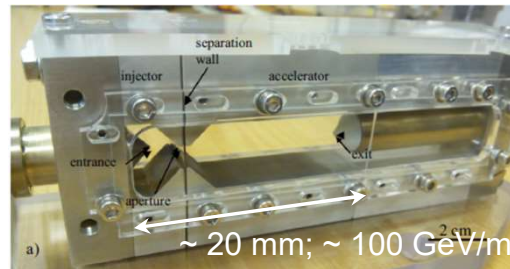
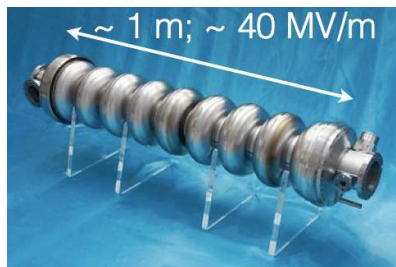
Daniel Symes

STFC Rutherford Appleton Laboratory, UK

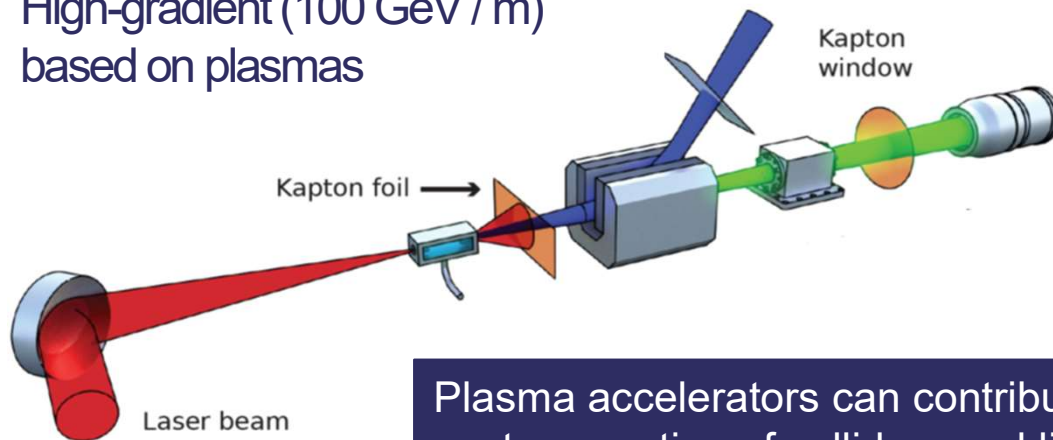




# A route to compact accelerators



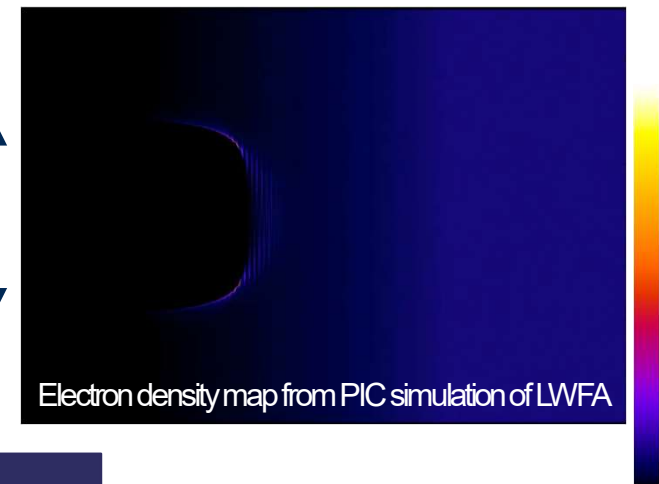
High-gradient ( $100 \text{ GeV / m}$ )  
based on plasmas



Plasma accelerators can contribute to the  
next generation of colliders and light-sources

## Laser wakefield acceleration

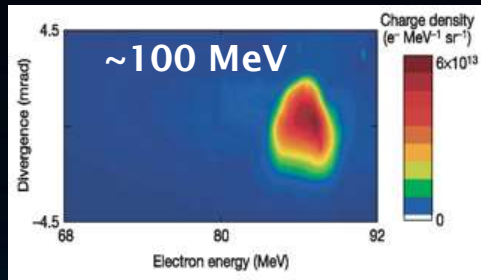
- cm-scale gas target
- Intense laser driver
- Multi-GeV electrons



# Laser-plasma accelerators go from 100 MeV to 8 GeV in a decade and half

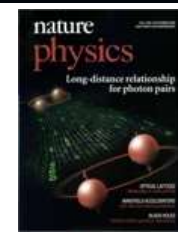
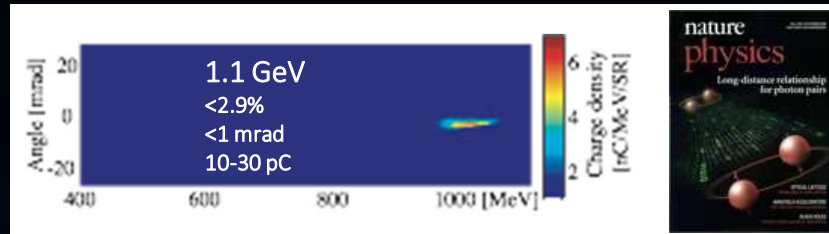
2004-2019: A success story

2004 result: 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)

2006 result: 40 TW laser, cm-scale plasma



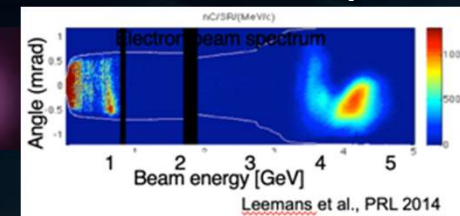
W.P. Leemans *et al.*, Nature Physics 2, p696 (2006)



2014 result: 310 TW laser, 9 cm-scale plasma



Experiment (spectrum)



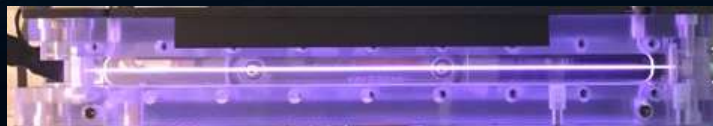
Leemans *et al.*, PRL 2014

2004

2006

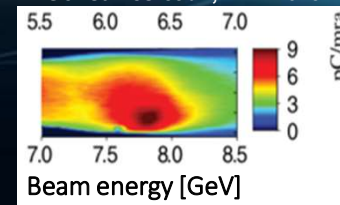
2019 result: 1 PW laser, 20 cm-scale plasma

2014



20 cm

Gonsalves *et al.*, PRL 2019



2019





# Main challenges for laser-plasma accelerators

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

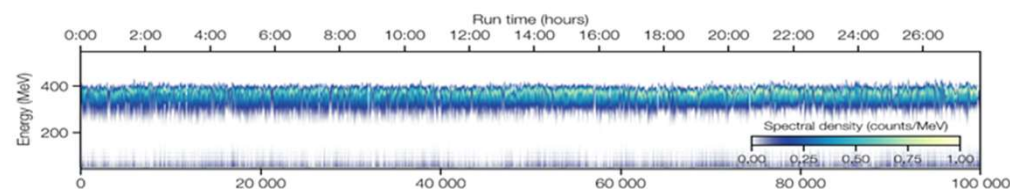
The ESPP Accelerator roadmap highlights research priorities for plasma acceleration

**Beam quality:** high brightness, low emittance, high energy with low spread **simultaneously**

**Beam stability:** Feedback and machine-learning optimization at **PW laser level**

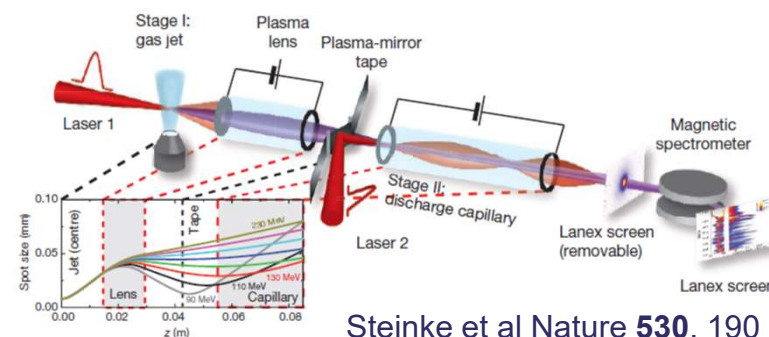
**Luminosity:** repetition rates **beyond kHz** with high wall-plug efficiency

**Energy:** Staging multiple modules to reach **100s GeV energies** for colliders (~30 years)



Maier et al PRX **10**, 031039 (2020)

**24 hour operation shown at DESY in 2020**



Steinke et al Nature **530**, 190 (2016)

**2-stage acceleration shown at LBNL in 2016**

# 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](http://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 Facility Schematic

## Top floor houses

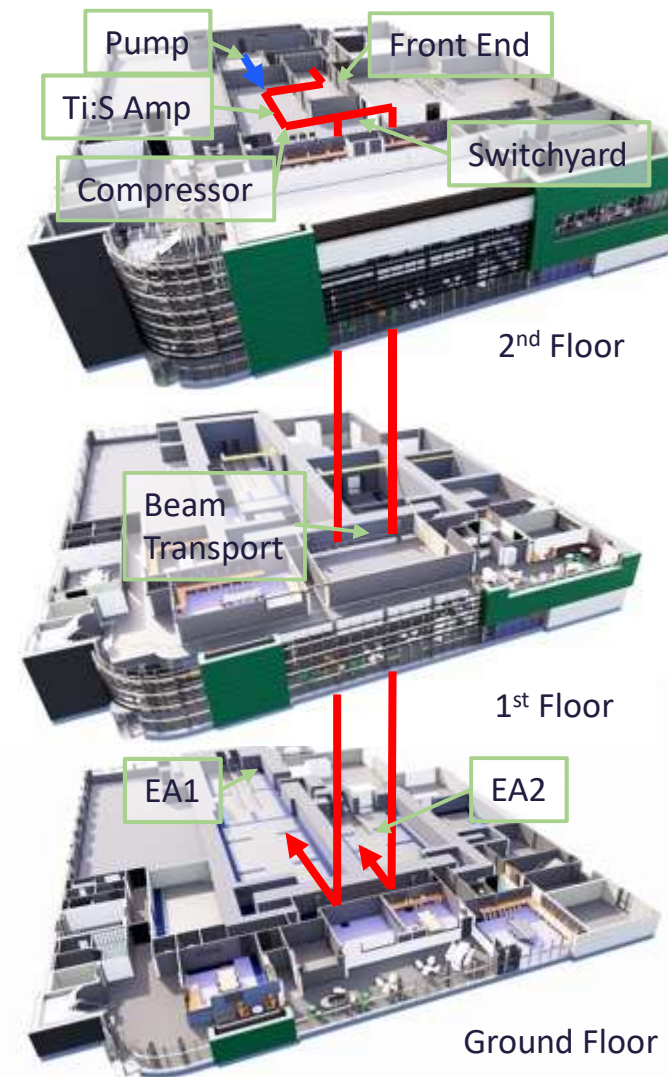
- 1 PW@ 10Hz Laser areas and laser control room.

Space for the addition of new laser systems: 2<sup>nd</sup> and 3<sup>rd</sup> synched beamlines

- Office space on 2<sup>nd</sup> and 1<sup>st</sup> floors

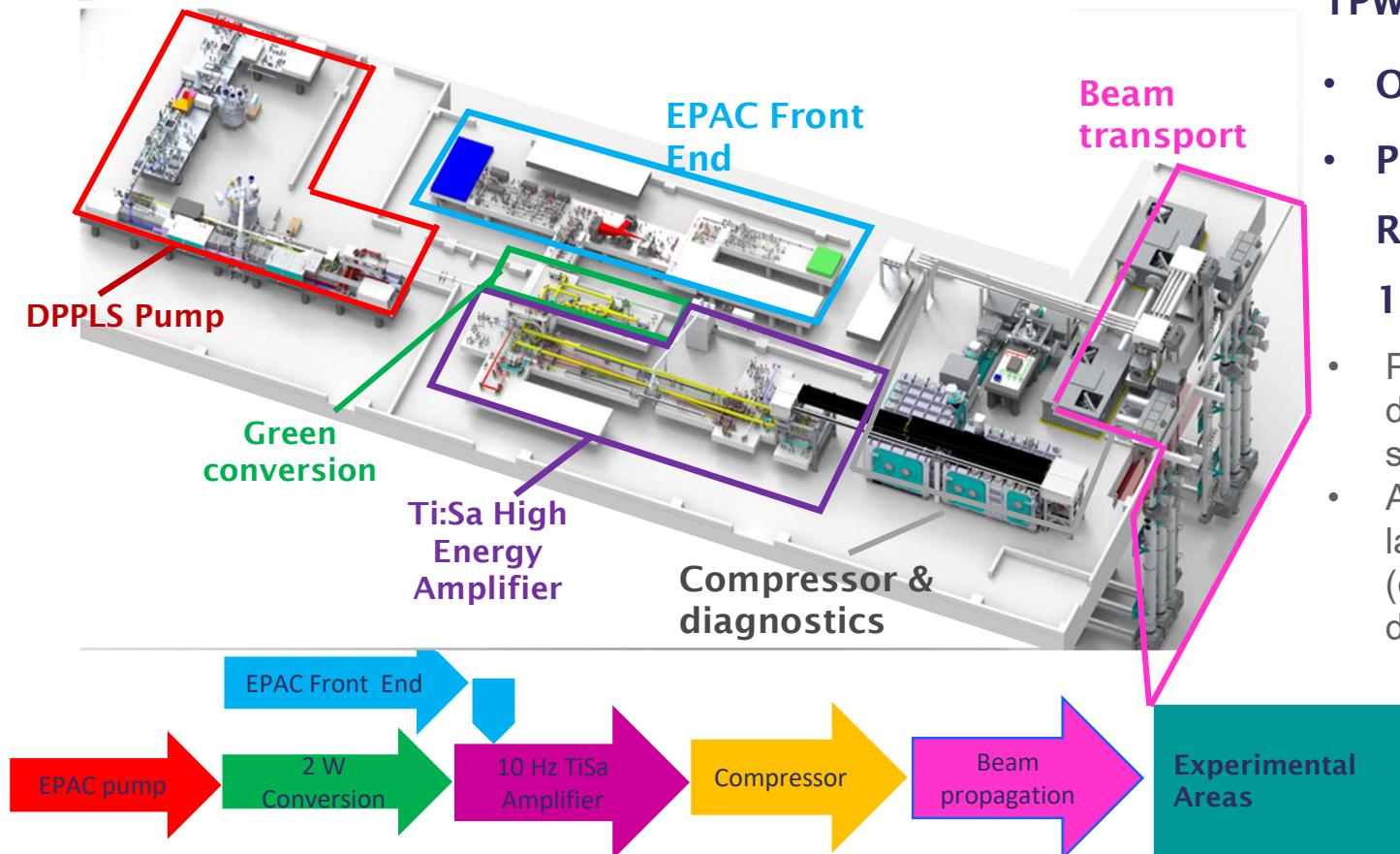
## Ground Floor houses three double height radiologically shielded experimental areas

- Experimental area 1 (EA1) ~38 m x 10 m,
- Experimental area 2 (EA2) ~18 m x 10 m
- Future experimental area (EA3)
- Control rooms and auxiliary labs and future cleanroom space and development laser labs





# EPAC Laser System



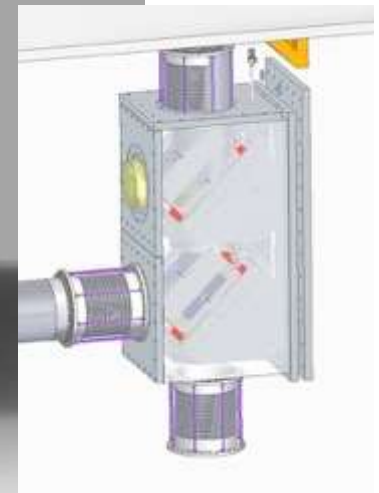
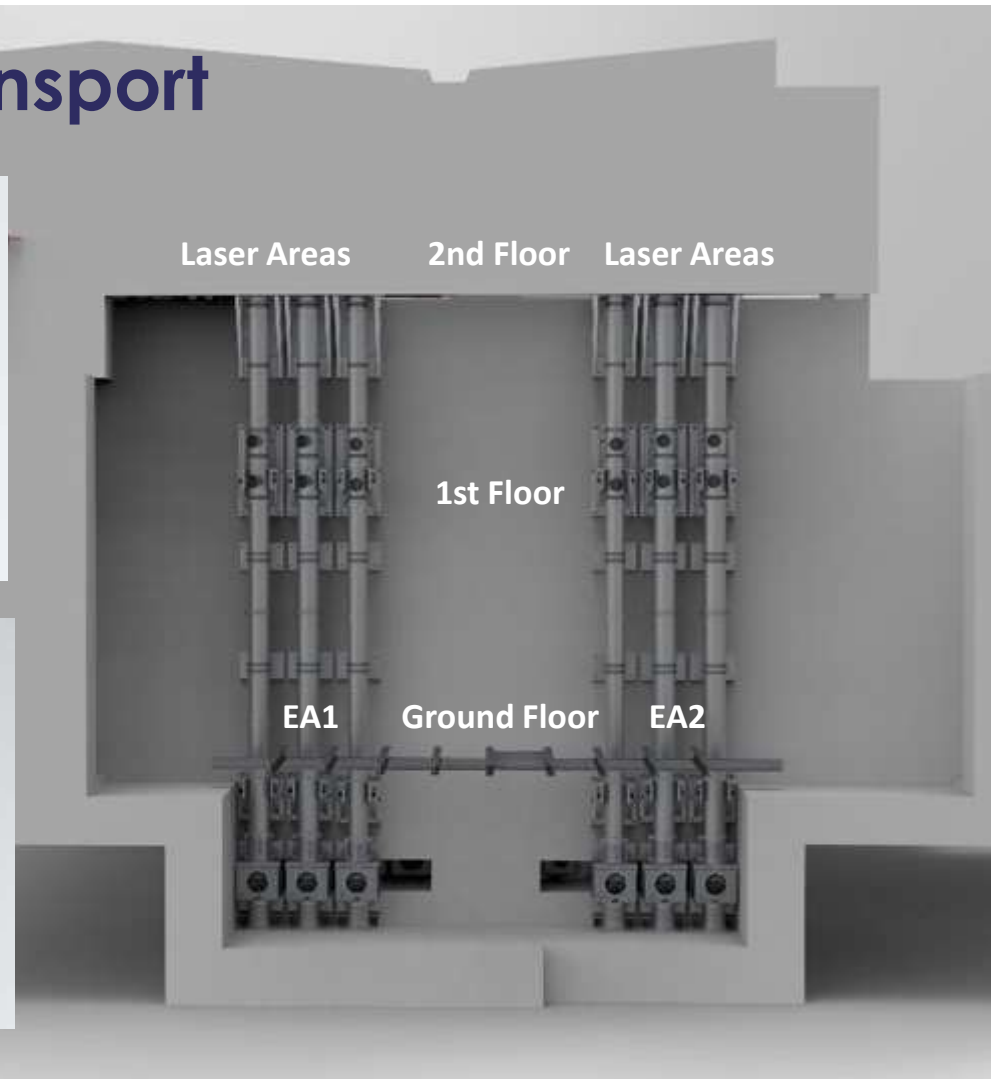
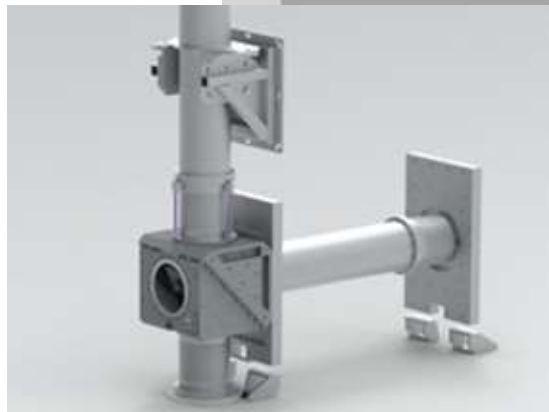
## EPAC specification

1PW@10Hz

- Output Energy 30 J
- Pulse duration  $\leq 30$  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)

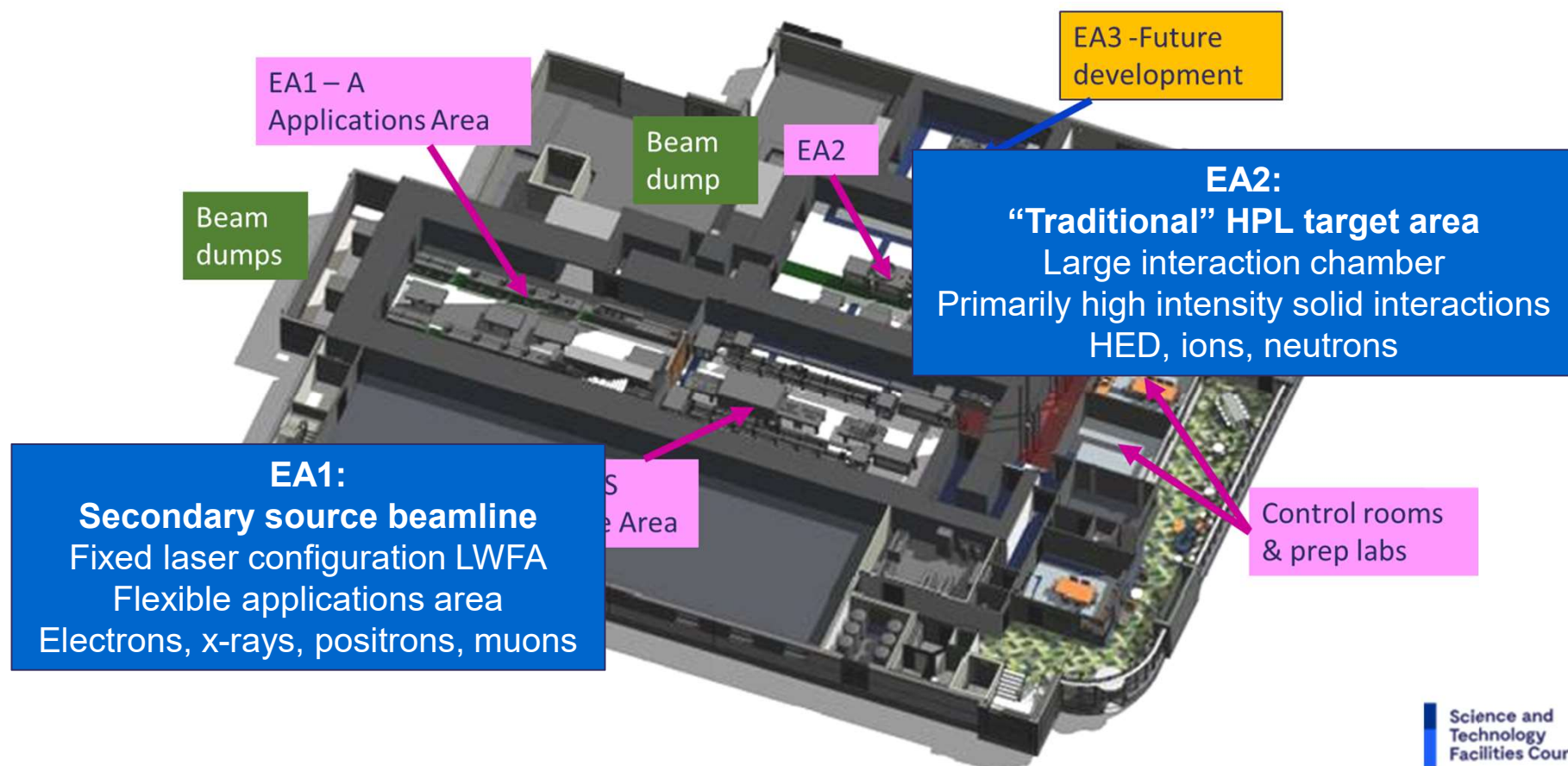


# Beam Transport



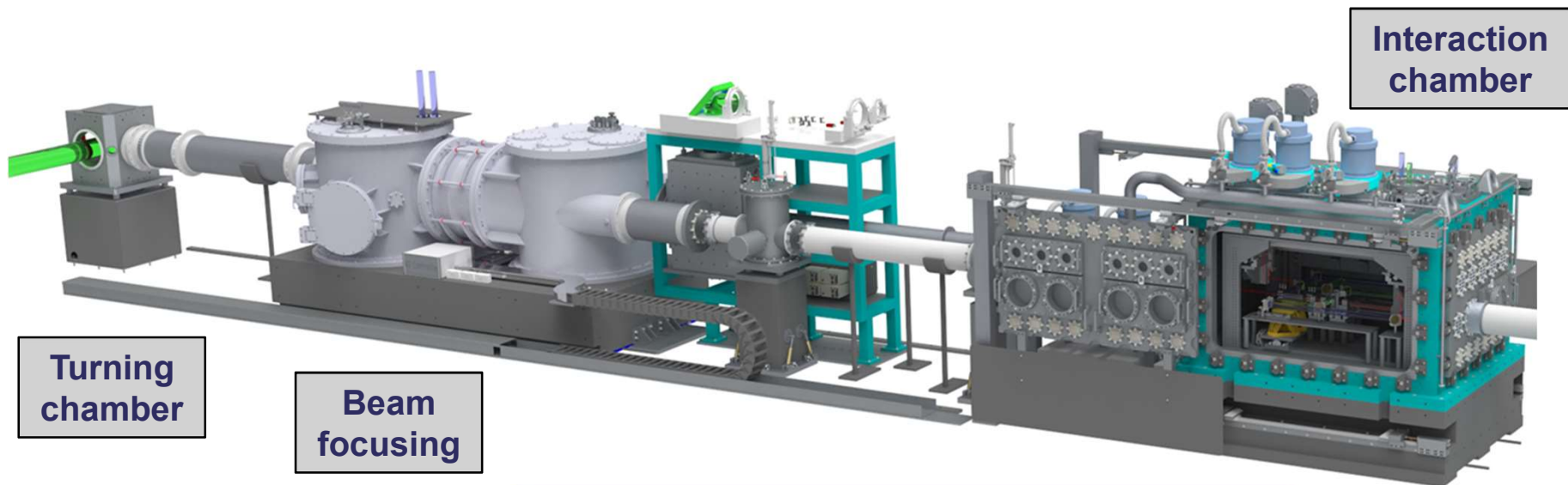


# Shielded target areas on the ground floor





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



**14 m OAP for 30 J**

Focused to relativistic  
intensity  $\sim 6 \times 10^{18} \text{ Wcm}^{-2}$

## Timeline:

**2023:** Chambers and large equipment delivered

**2024:** Commissioning with internal laser

**2025:** Pulsed beam and LWFA commissioning

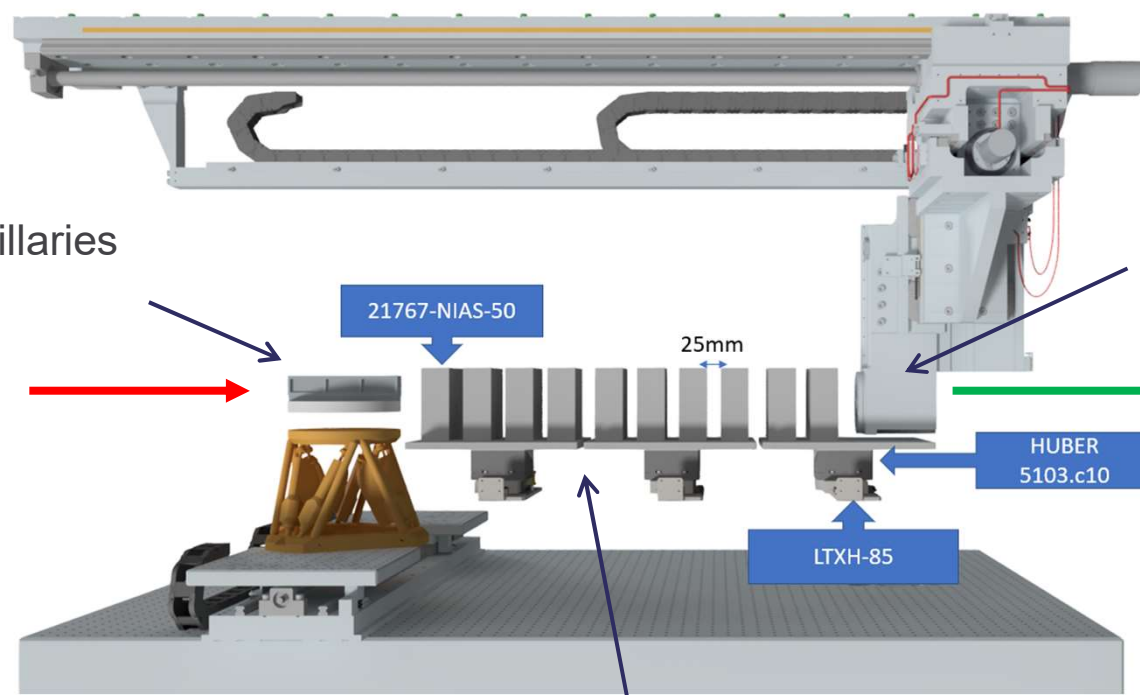
**2026:** Operational user facility



## Interaction chamber houses LWFA, diagnostics, and quadrupole magnets

Gas targets:  
Jets, cells, capillaries  
~cm to 10s cm

LASER



Beam and  
target  
camera

ELECTRONS  
& X-RAYS

Quadrupole system for  
beam capture and focusing



## EA1 – Application area

### Secondary source parameters:

100 MeV – 10 GeV electrons

50 keV – 10 MeV tunable x-ray radiation

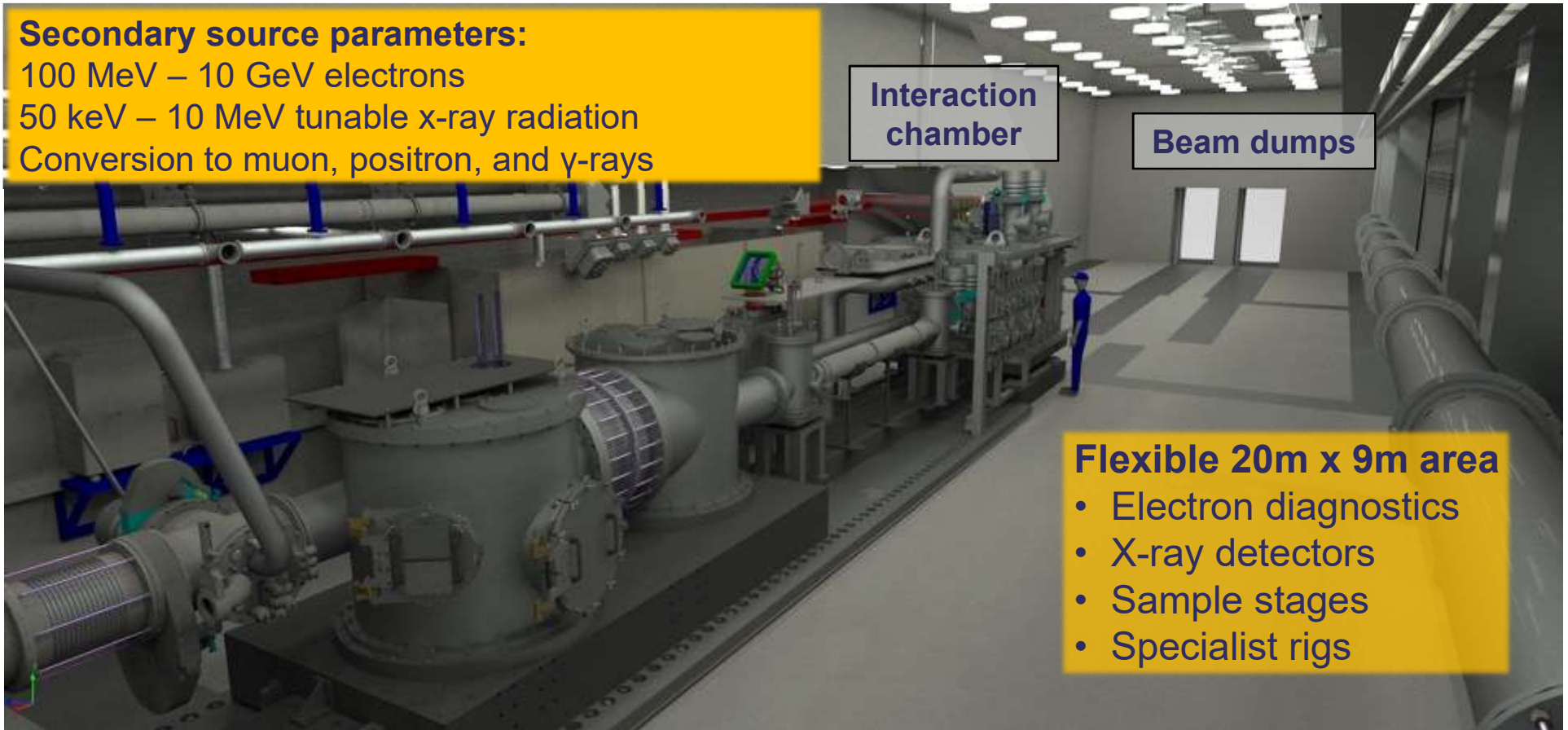
Conversion to muon, positron, and  $\gamma$ -rays

Interaction  
chamber

Beam dumps

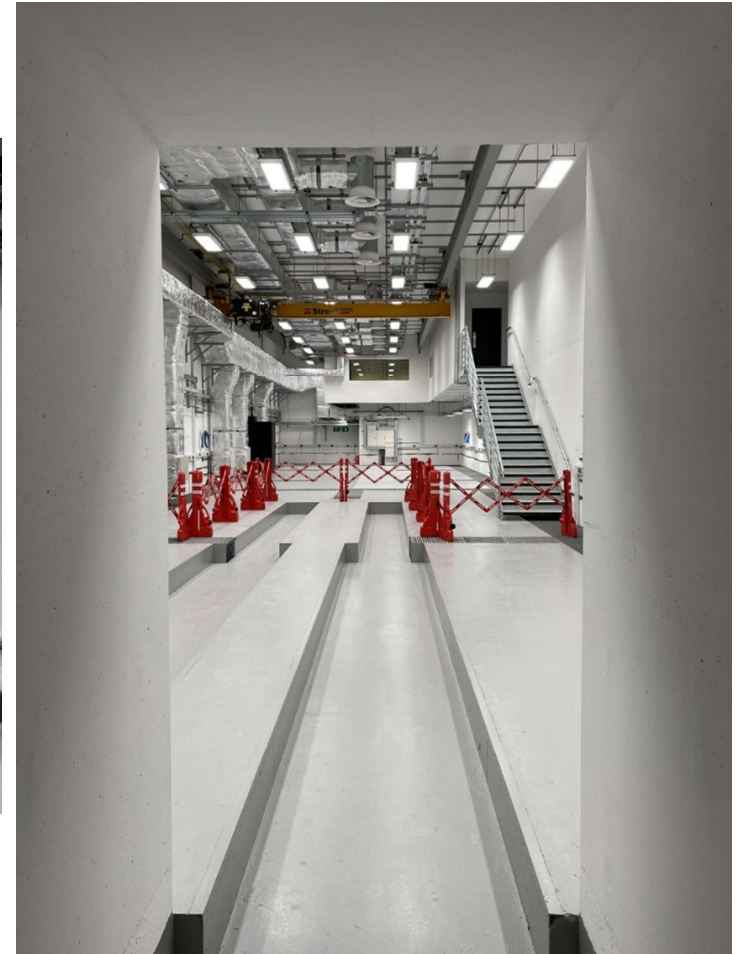
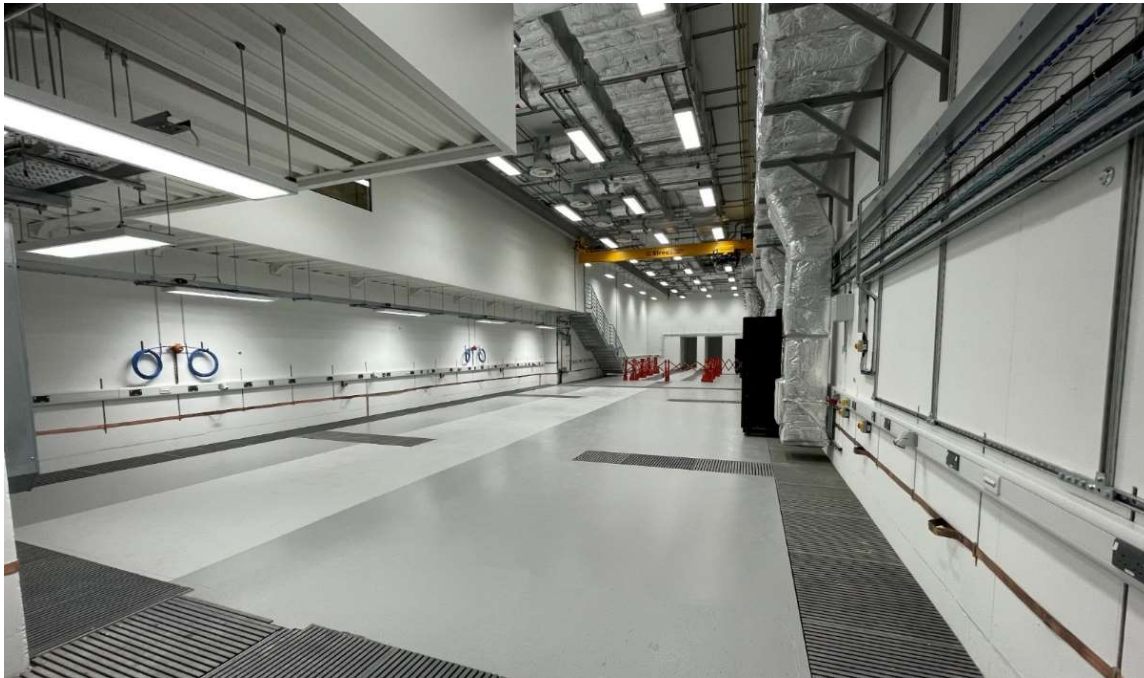
### Flexible 20m x 9m area

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





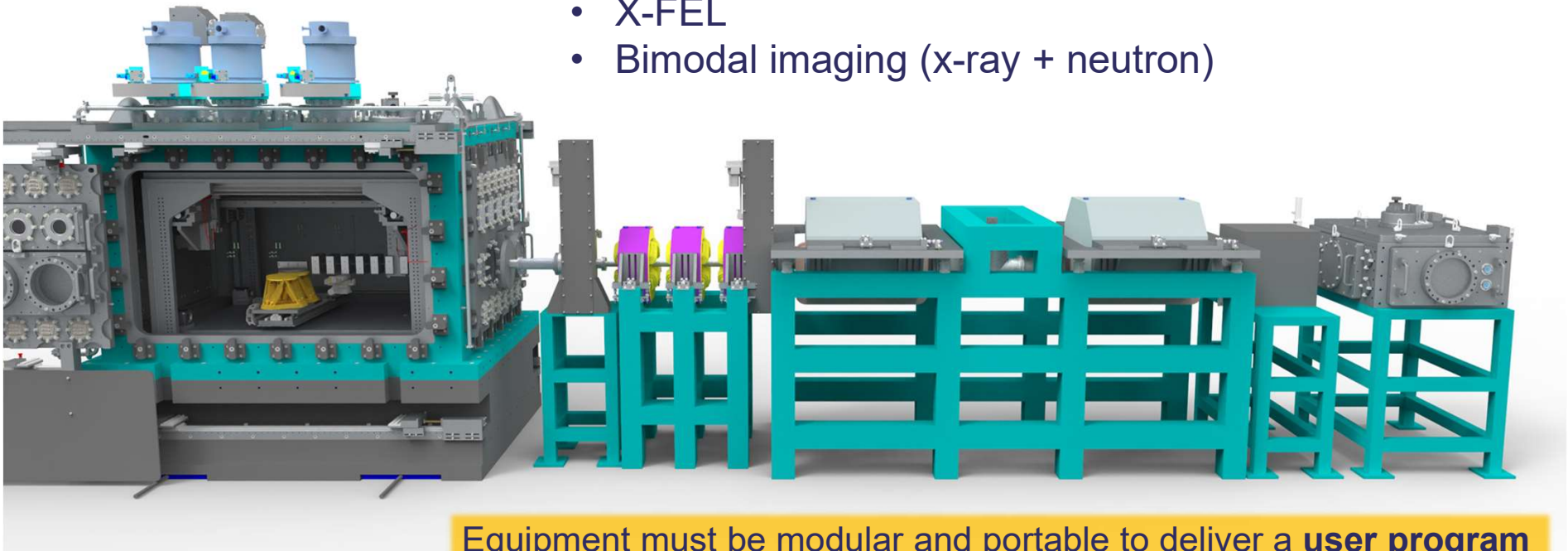
## EA1 internal view





# EA1 beamline requirements

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



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



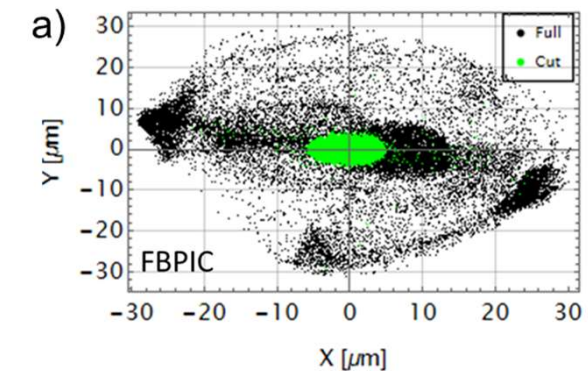
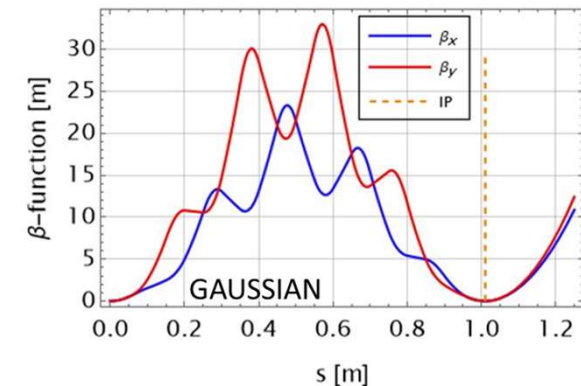
# Start-to-end simulations

- Designing **beamlines** for various scenarios expected in EA1
- **Start-to-end** simulations – PIC for LWFA + magnet tracking codes
- Gaussian beams are **not** representative because of LWFA energy spread

## Difficulties:

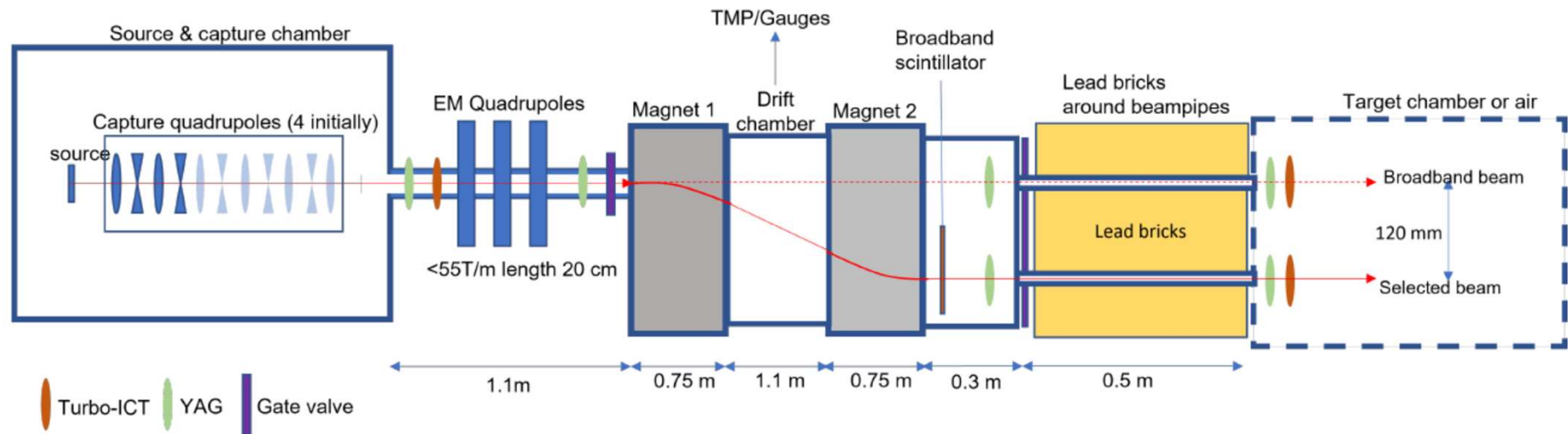
- Converting PIC output into useable input to tracking codes
- **High energy** – most LWFA beamline designs have been at 100s MeV level
- **Detail** – most published work does not fully analyse the system
- **Flexibility** – EPAC is driven by user demands, it needs to offer a choice of energy and sample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

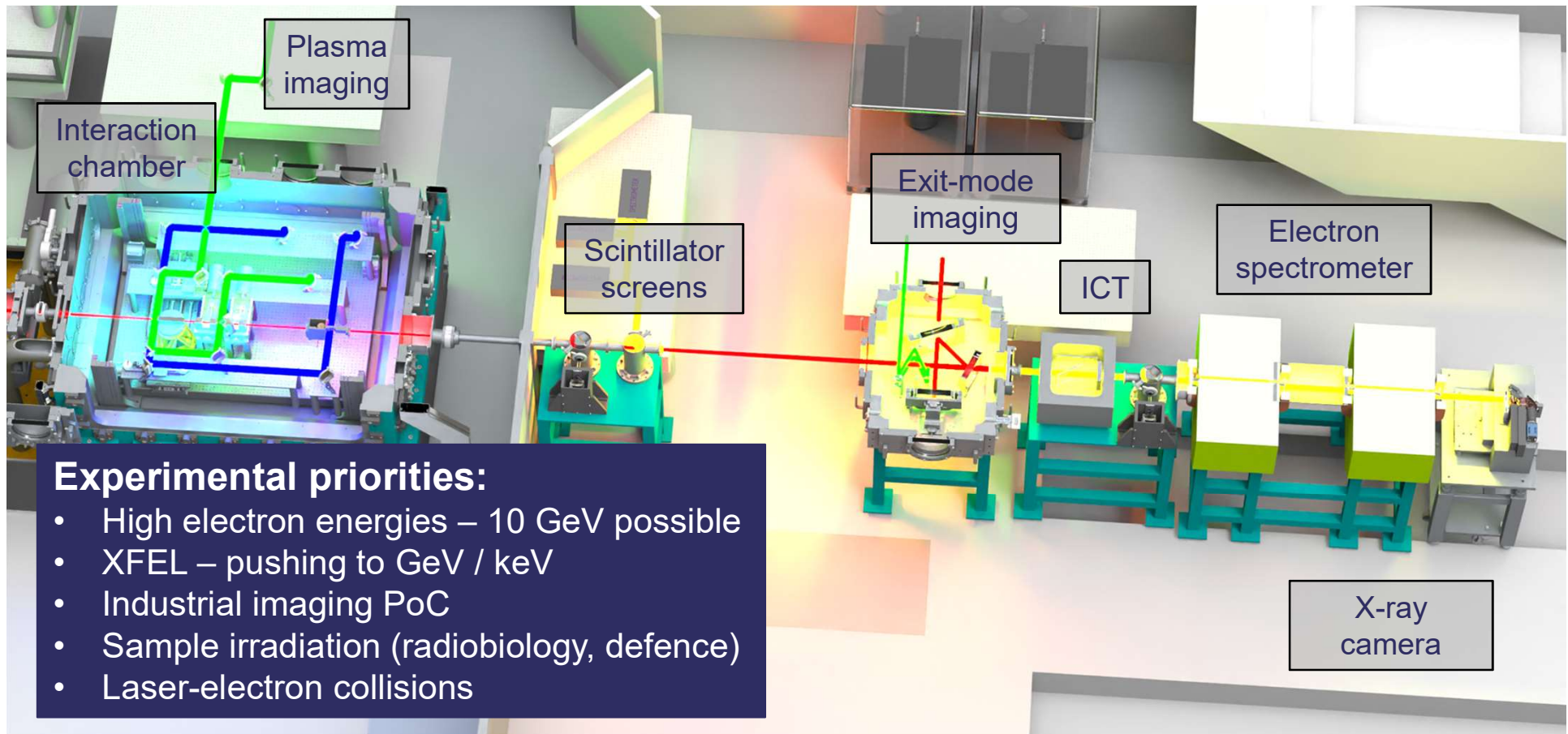
Use the EM quad triplet to form focus at the required distance:

**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



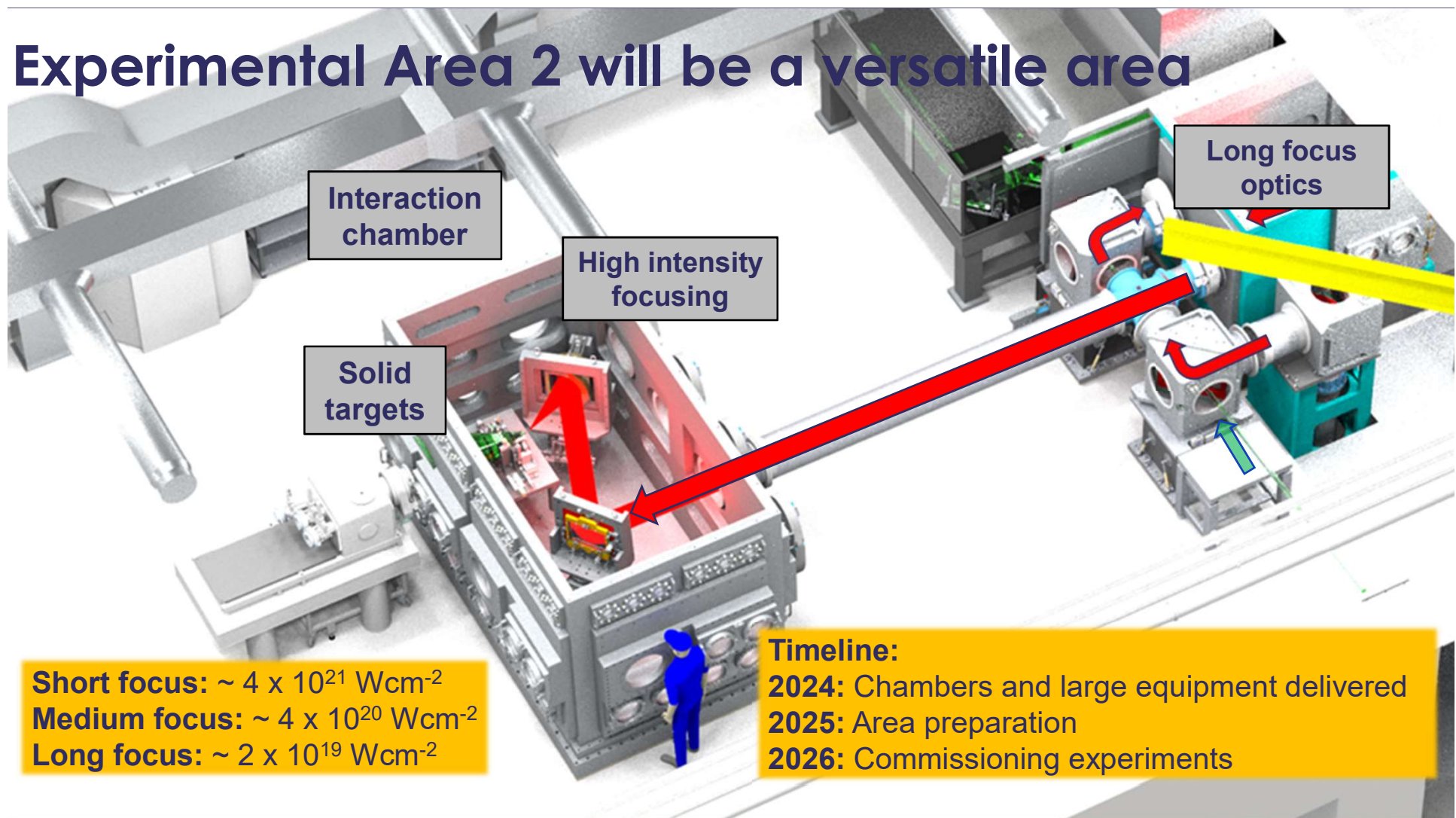
## Experimental Area 2 – Overview

### 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

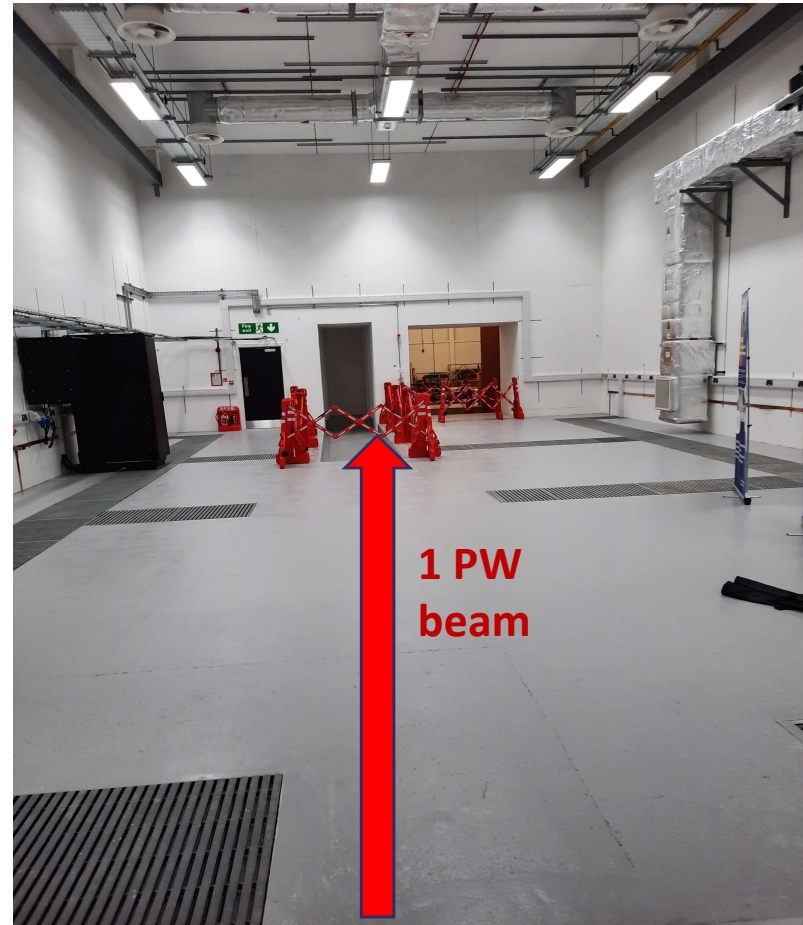
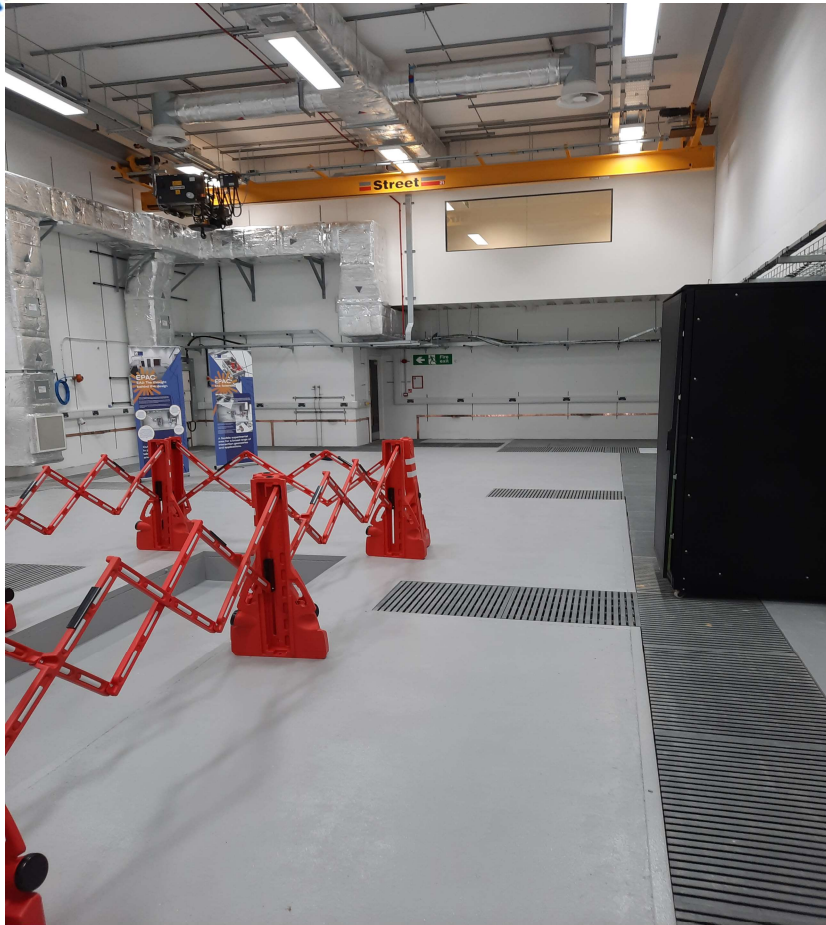


## Experimental Area 2 will be a versatile area





## Experimental Area 2 – Internal view

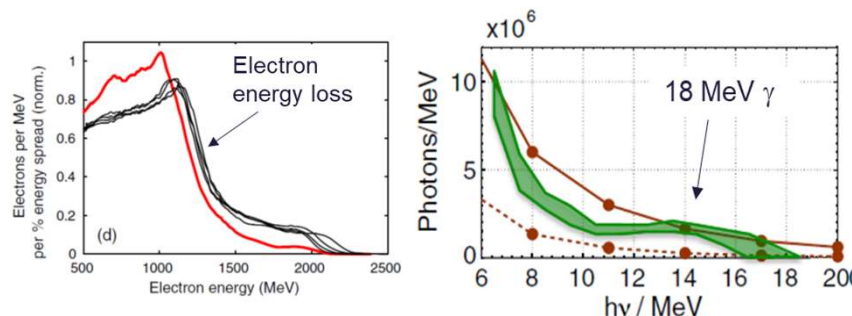
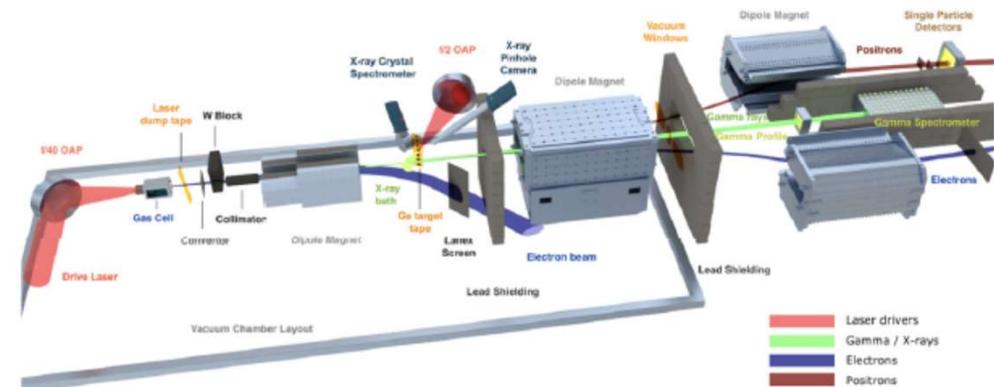




# Fundamental science using LWFA beams

## Pioneering dual beam experiments with the Gemini laser

- Multi-GeV e- colliding with  $10^{21} \text{ Wcm}^{-2}$  laser focus
- Measurable quantum-electrodynamic effects: radiation reaction, pair production, photon-photon scattering
- Non-linear Inverse Compton Scattering



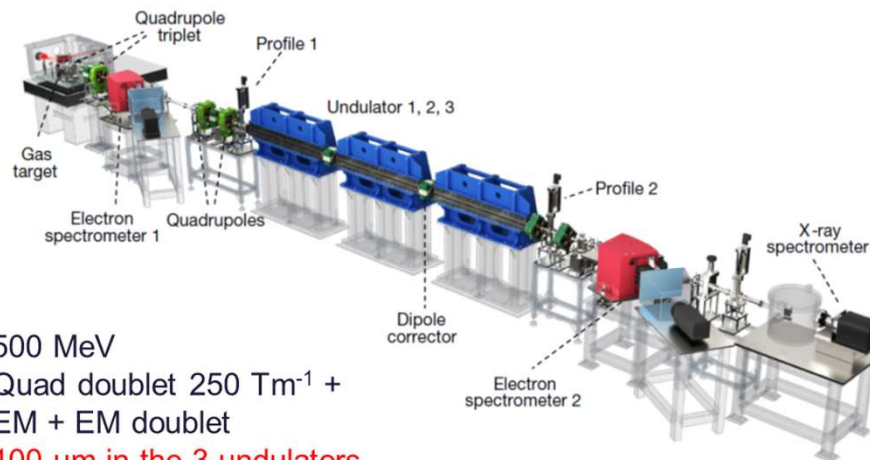
**Beamline arrangement for dual beam experiments**  
Configuration can easily be switched for laser-e-, laser- $\gamma$ , and  $\gamma$ - $\gamma$  collisions

EPAC will have much better stability & higher repetition-rate

Cole 2018, PRX **8**, 011020; Poder 2018 PRX **8**, 031004;  
Sarri 2014 PRL **113**, 224801; Kettle 2021, NJP **23**, 115006

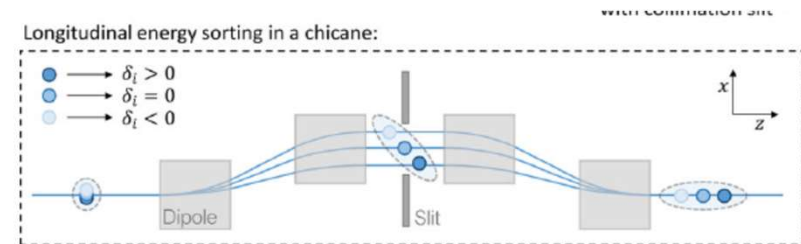


# LWFA driven Free-Electron-Laser

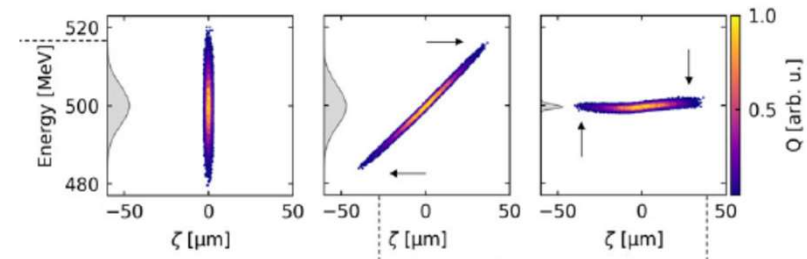


- 500 MeV
- Quad doublet  $250 \text{ Tm}^{-1}$  + EM + EM doublet
- 100  $\mu\text{m}$  in the 3 undulators

Wang 2021, Nature **595**, 516; Pousa 2022 PRL **129**, 094801



## Decompress & dechirp



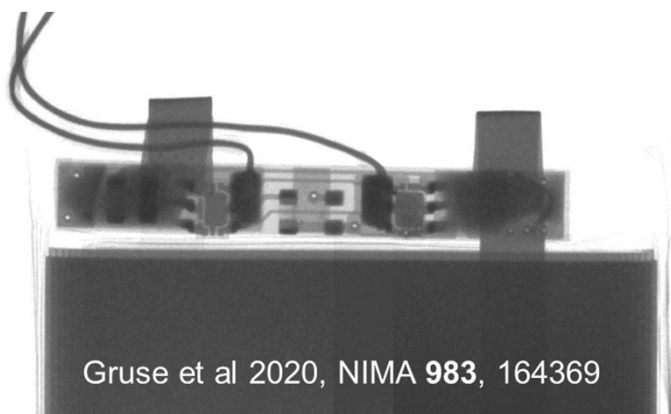
## LWFA and compact undulators can shrink size and cost but significant R&D is required

- 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  
Preliminary calculations suggest FEL gain within 5 m

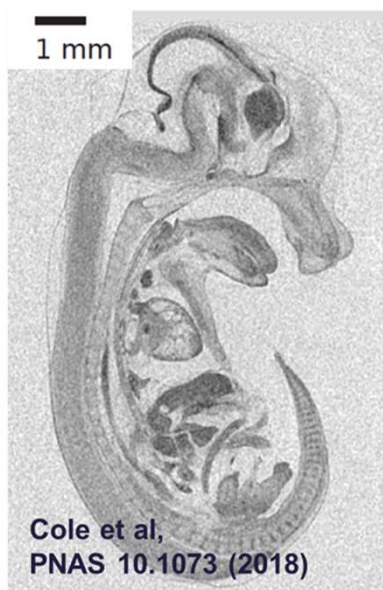


# Proof-of-concept x-ray imaging using LWFA beams generated with Gemini



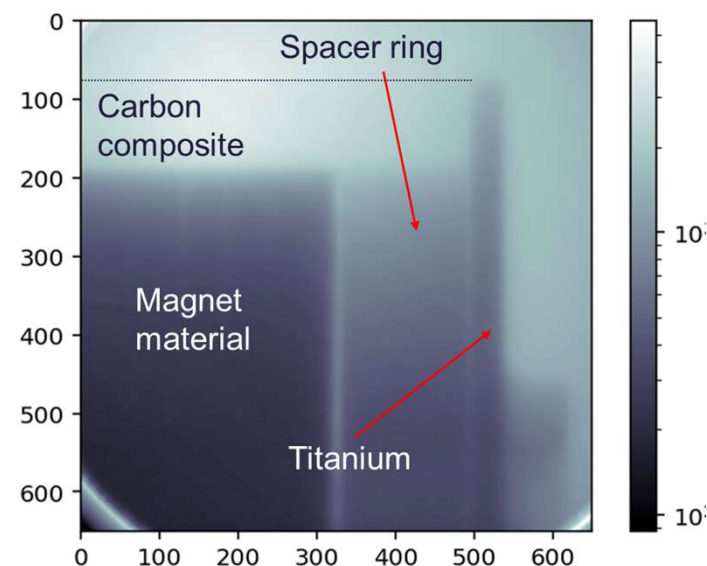
Gruse et al 2020, NIMA **983**, 164369

Radiography and  $\mu$ CT at  
20 keV, 30  $\mu$ m resolution



Cole et al,  
PNAS 10.1073 (2018)

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



Radiography with MeV brems.  
~400  $\mu$ m resolution



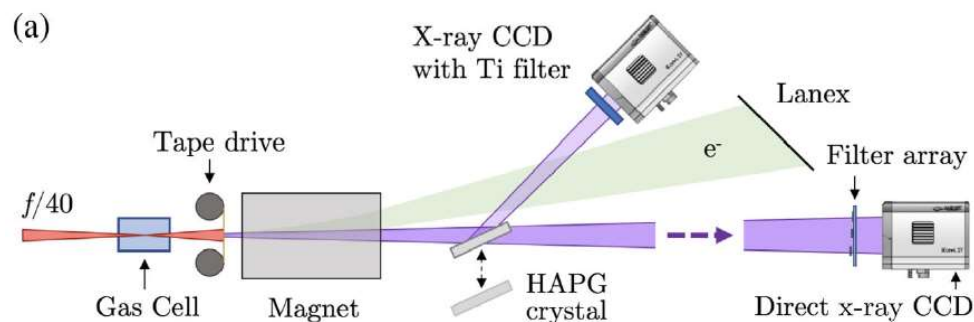
Rolls-Royce



Science and  
Technology  
Facilities Council

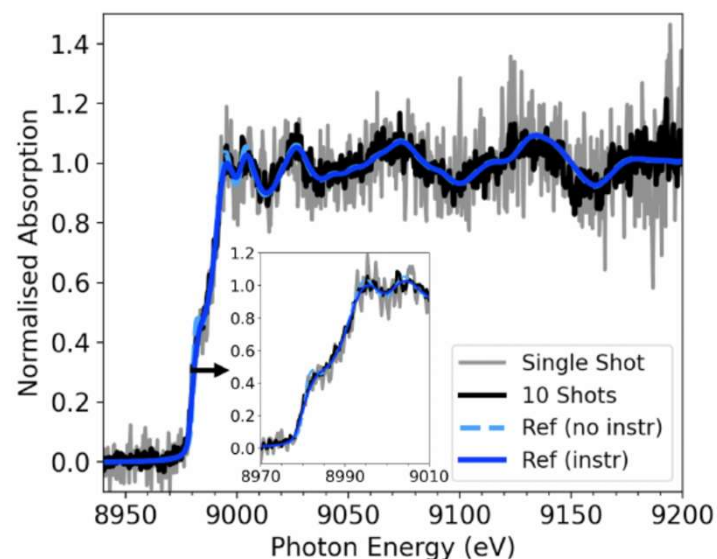


# Ultrafast XAS measurements with betatron



- **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

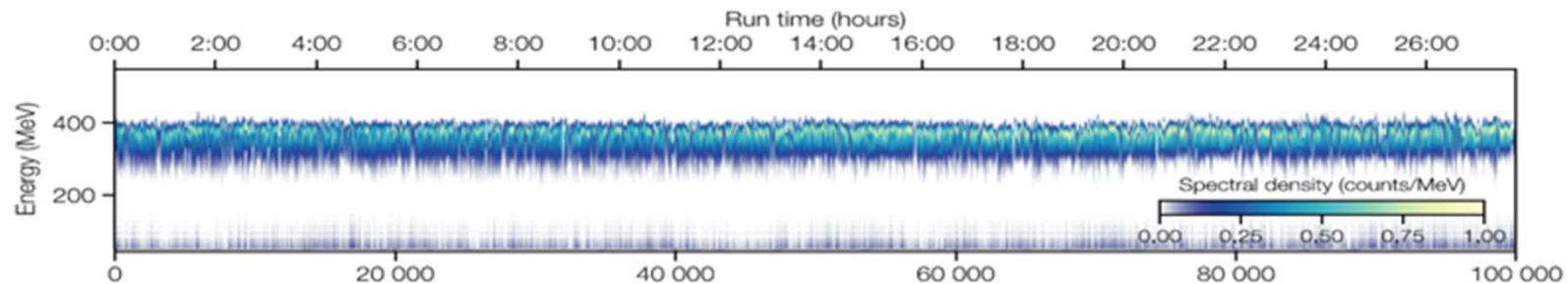


Single-shot XANES and EXAFS of Cu edge

Kettle 2019, PRL **123**, 254801; Kettle 2022 submitted



# Stable LWFA operation over extended periods



## DESY beamline proved LWFA can be stable

Fluctuations correlated to laser and target parameters and can be stabilised with feedback loops

## Electron beam energy over 24 hours

Maier et al PRX **10**, 031039 (2020)

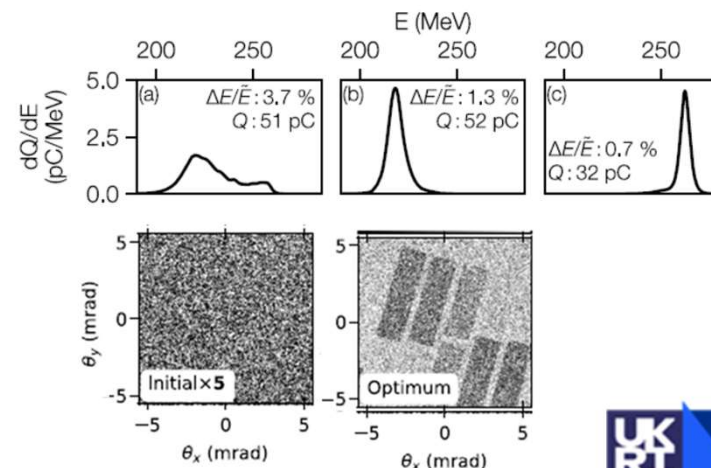
## Optimization using machine-learning techniques

Laser pulse shaping and varying gas target parameters optimises the specified property (e.g. electron energy, x-ray flux etc)

## Bayesian optimisation of LWFA

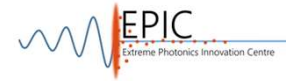
Shaloo et al Nature Comm. **11**, 6355 (2020);

Jalas et al PRL **126**, 104801 (2021)

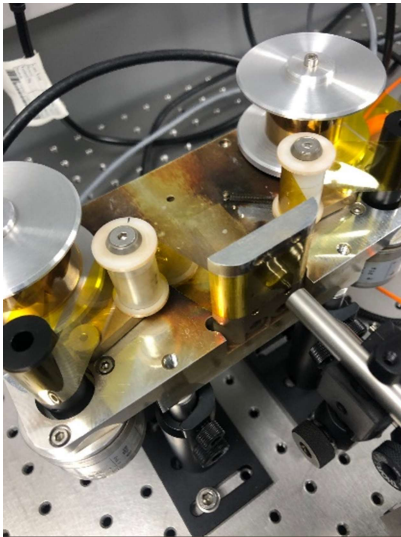




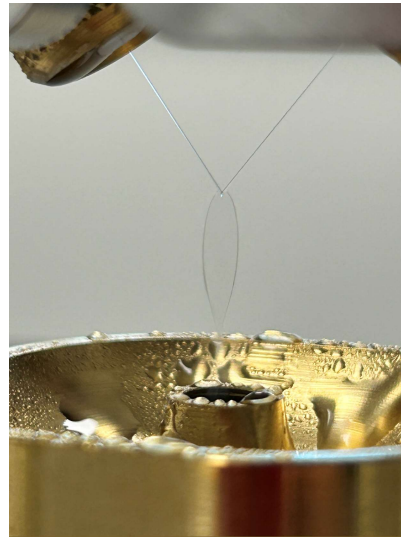
# High rep-rate targetry



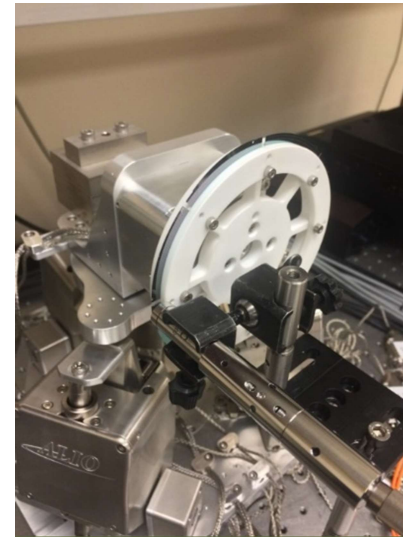
To meet the increasing rep rate there is a change in focus from single component manufacture and machining to batch and high rep rate production. Collaborations and developments internally and externally are helping us to meet this challenge



Tape targets with a 2µm position stability



Liquid sheets for plasma mirrors and targets



MEMS fabrication for mass-produced complex targetry





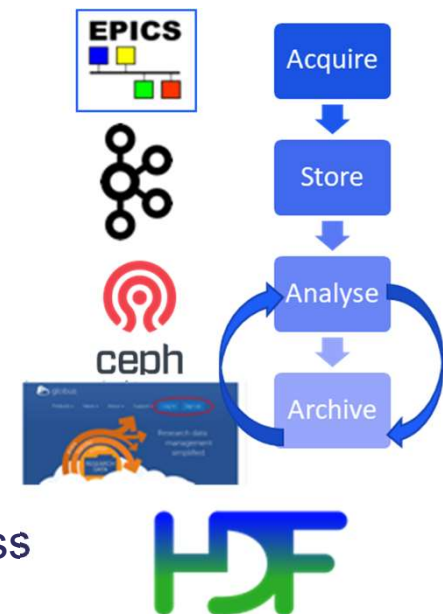
# Data acquisition and management

## 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



## A large (international) collaboration is involved in building EPAC





# @ 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€





# 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

