EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA project and the UK plan to develop a centre for applications EuPRAXIA beamlines

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On behalf of UK members of EuPRAXIA: ASTeC, CLF, ICL, Liverpool, Manchester, Oxford, QUB, SCAPA, York

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

Outline

- Introduction
- Plasma Wakefield Accelerator Steering Committee (PWASC)
- Existing and future facilities in the UK
- EuPRAXIA Excellence Centre for Advanced Applications Beamlines in the UK

Please refer to

- Plenary talk by Rajeev Pattathil “A new advanced facility for applications of laser-driven accelerators”
- Plenary talk by Ralph Assmann “Status and future perspectives of the EuPRAXIA project”
- WG4 talk by Maria Weikum “Science applications for the European accelerator research infrastructure EuPRAXIA

The field of plasama wakefield accelerators in the UK

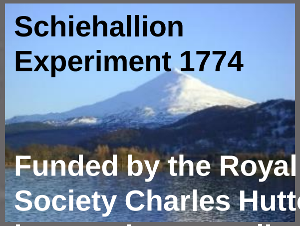
- The UK groups, in collaboration with their international colleagues, have strong record of developing high-quality plasma-accelerated electron beams, including: the first demonstration of narrow-band electron beams, the first generation of of GeV beams, the successful demonstration of electron acceleration by the AWAKE collaboration, and the first demonstration of the plasma photocathode scheme.
- The UK groups have also been strongly involved with developing the applications of these beams. For example, applications to: betatron radiation to tomographic imaging of medically-relevant samples, security, electron-positron plasma generation, strong-field QED experiments, tests of radiation reaction.

PWASC

- Since 2016 the UK research in the area of plasma wakefield accelerators has been nationally coordinated by PWASC, see http://pwasc.org.uk/), which represents groups at 10 universities (Imperial College London, Lancaster, Liverpool, Manchester, Oxford, Queen's University Belfast, St. Andrew's, Strathclyde, University College London, and York), as well as the Accelerator Science and Technology Centre (ASTeC) and the Central Laser Facility (CLF).
- PWASC, in consultation with all UK researchers working in the area of plasma wakefield accelerators, have developed a roadmap for UK plasma accelerator research http://pwasc.org.uk/uk-roadmap-development The roadmap concludes with recommendations for research funding, provision of experimental and computational facilities, training, and international collaboration.

SUPA: Scottish Universities Physics Alliance

SUPA | Physics Scotland



Schiehallion Experiment 1774

Funded by the Royal Society Charles Hutton invented contour lines

University of Aberdeen

University of Dundee

University of St Andrews

SCAPA

University of Glasgow

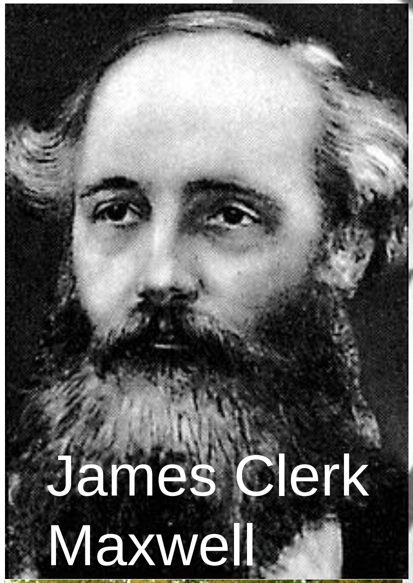
University of the West of Scotland UWS

University of Strathclyde Glasgow

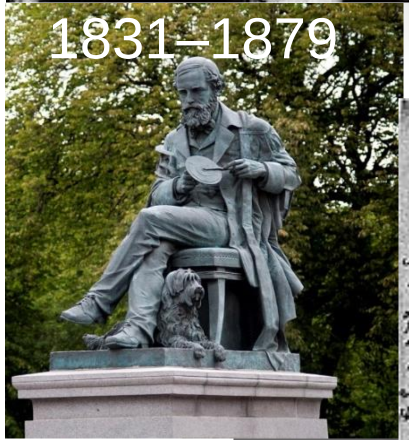
Heriot Watt University

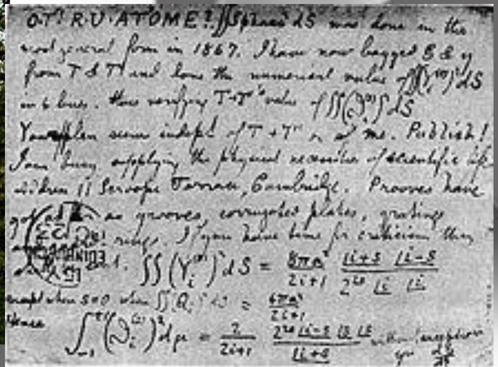
The University of Edinburgh

SUPA: largest Physics Alliance in the UK consisting of 8 Scottish universities.



James Clerk Maxwell 1831–1879

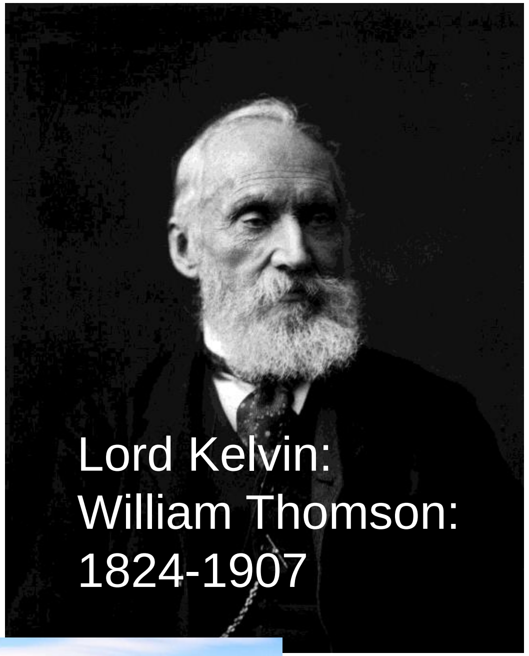




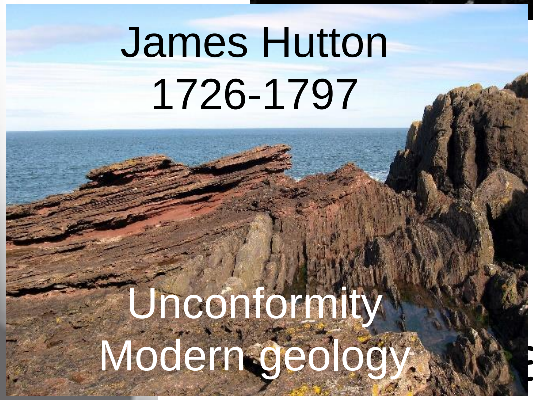
Maxwell's equations:

$dF = 0$

$d * G = j$



Lord Kelvin: William Thomson: 1824-1907



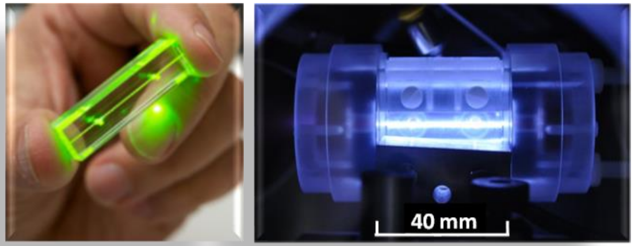
James Hutton 1726-1797

Unconformity Modern geology

The Scottish Centre for the Application of Plasma-base Accelerators

http://www.scapa.ac.uk/

- Expansion of **ALPHA-X** laser-plasma accelerator facilities at Strathclyde with newly constructed laboratories
- **Applications, Research & Development**.
- Knowledge Exchange & **Commercialisation** opportunities
- Engagement in UK and European continent (ELI, Laserlab, AWAKE, EuPRAXIA)
- **Training** e.g. Doctoral training, Undergraduate projects
- **3 shielded areas** containing **7 accelerator beam lines**
- High-intensity femtosecond laser systems:
  - a) **350 TW** (with provision for expansion) @ **5 Hz**
  - b) **40 TW @ 10 Hz PRF**,
  - c) **sub-TW @ kHz PRF.**
- High-energy **proton, ion, electron, positron** bunches, High-brightness **THz, X-ray and gamma-ray** pulses
- Control of particle and radiation beam polarisation.
- Attosecond pulses
- Probe beams
- Undulators
- Beam transport

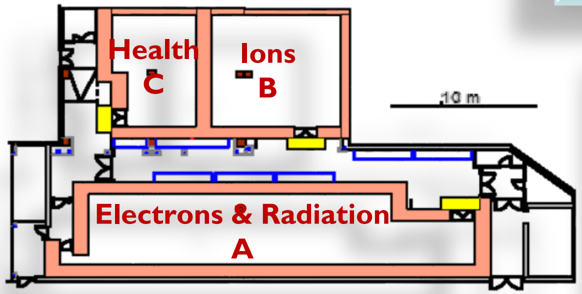


Compact GeV electron accelerator and gamma-ray source

EuPRAXIA: Applications programme (gamma rays and positrons), and development of attosecond sources, plasma undulators and FEL

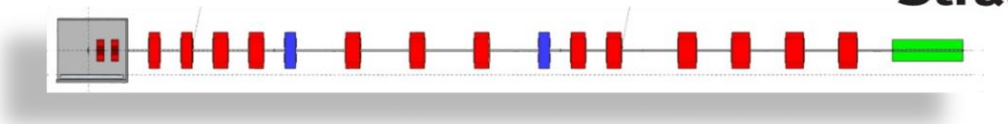
APPLICATIONS

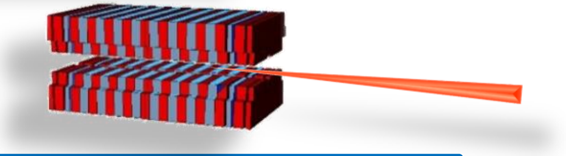
- Radiobiology
- Ultrafast Probing
- High-Resolution Imaging
- Radioisotope Production
- Detector Development
- Radiation Damage Testing



FEL test beamline at SCAPA (A3)

Beamline to transport electrons from LWFA to undulator





Laser parameters

Peak power	350 TW
Central wavelength	800 nm
Energy	9 J
Pulse duration (FWHM)	25 fs
Pulse rep. rate	5 Hz

Bunch parameters: PIC simulations

Energy range	1 - 4 GeV
Norm. emittance (x,y)	0.4 µm
RMS energy spread	1 %
Abs. bunch length	0.3 µm (1 fs)
Bunch charge	20 pC
Divergence	<1 mrad

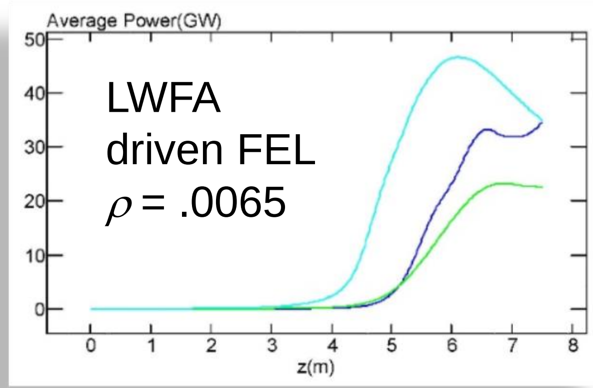
ALPHA-X Undulator [1] parameters (measured [2])

No. of Periods	100 × 2
Period	15 mm
Operating gap	7.2 - 3.5 mm
K value range	0.3 - 1.0

Water window femtosecond pulse FEL and two-colour fs synchrotron source

Current best measured parameters

Energy	800 MeV
Norm. Emittance	< 1 π µm
RMS Energy Spread	< 0.35 - 3.5%
Bunch Length	≈ 0.3 µm (1 fs)
Bunch Charge	10 - 20 pC
Divergence	1 mrad



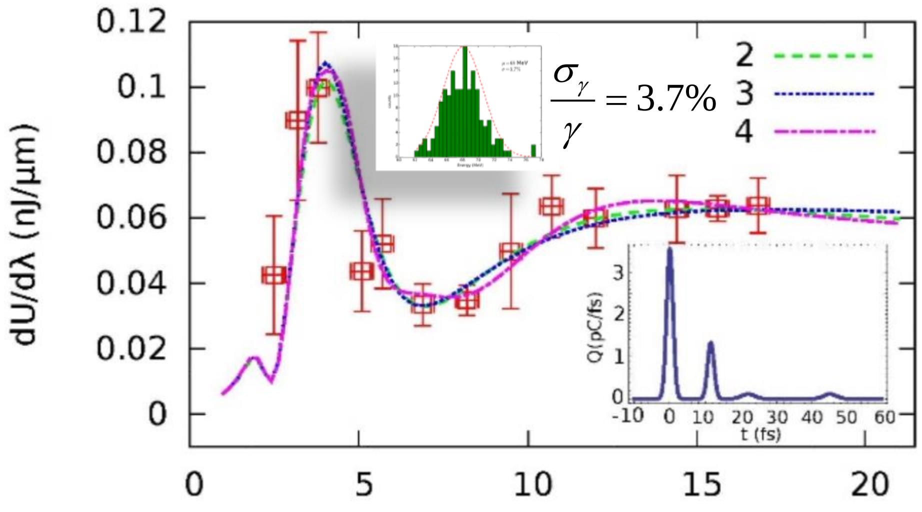
Main challenges:

- Divergence
- Energy spread
- Removal of laser light prior to undulator
- Control of the isochronicity/momentum compaction (R_{56})
- Control of emittance growth (chromatic effect) – common to large energy spread transport lines [3]
- Use experimentally measured parameters as a basis for Cockcroft beamline design

[1] D.A. Jaroszynski et al., Royal Society Transactions, (2006)
[2] B. J. A. Shepherd & J. A. Clarke, *Nucl. Instr. Meth. Phys. Res. A* (2011)
[3] T. André, *Nature Communications* (2018)

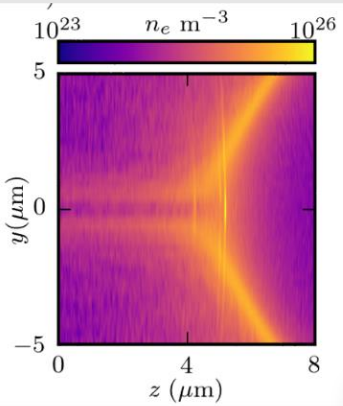
Towards attosecond bunches

Coherent Transition Radiation spectrum

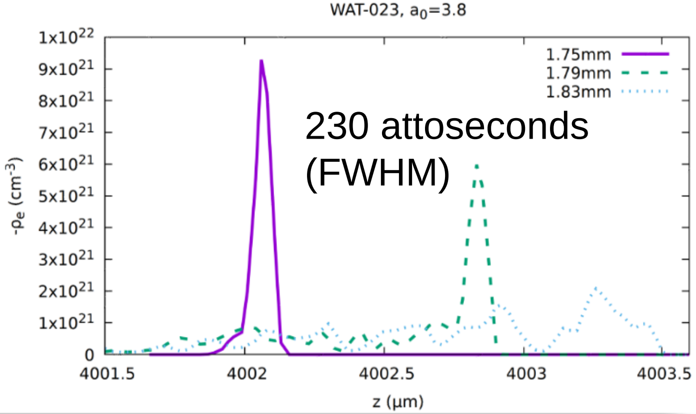


Islam et al., NJP 2015

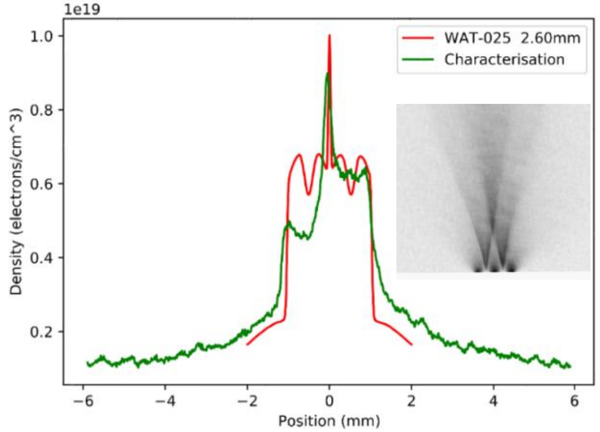
Measured Ultra-short bunches: ~ 1 fs at source – Peak current several kA and THz pulse – 1 MW peak power



S.M Yoffe et al., SPIE 2019



Kornaszewski et al., SPIE 2019

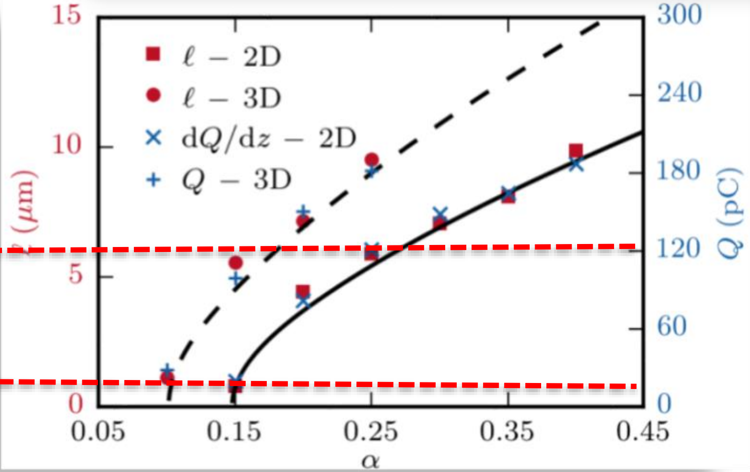


Gas jet simulations and density measurements: medium fpr attosecond bunch generation

M.P. Tooley et al., PRL 2017

8 kA 15 fs

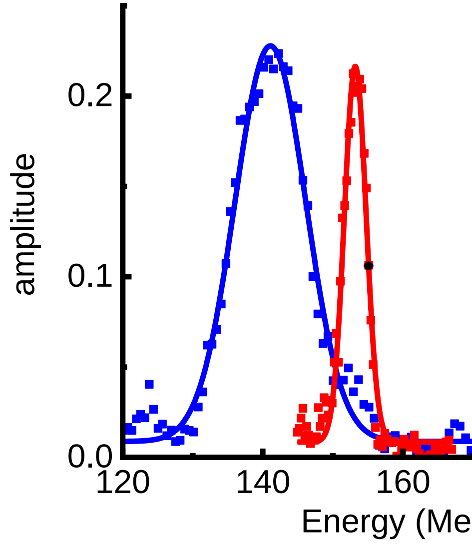
>10 kA 260 as



EuPRAXIA programme: Towards a high brightness attosecond source

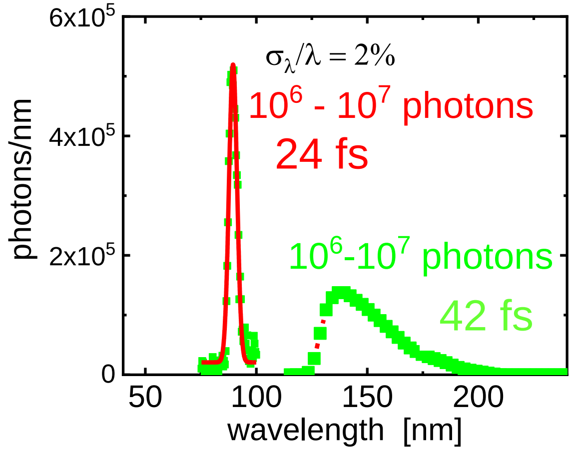
XVUV undulator measurements: towards LWFA-driven attosecond synchrotron and FEL sources

10^7 photons **predicted**



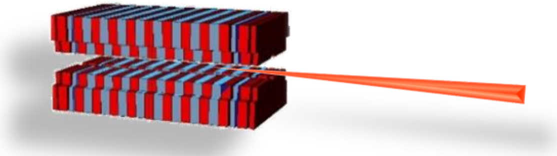
$$\frac{\sigma_\lambda}{\lambda} = 2\% \Rightarrow \frac{\sigma_\gamma}{\gamma} = 0.87\%$$

10^7 photons **measured**

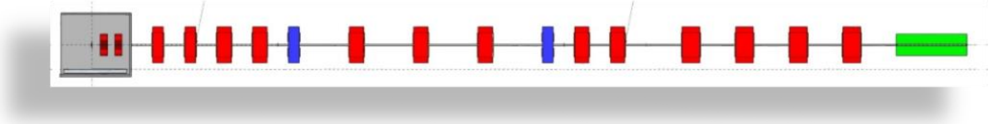


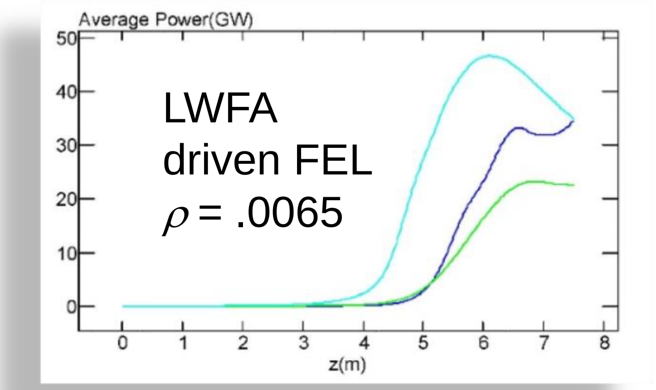
Anania, et al., Applied Physics Letters 2014

Jaroszynski et al., SPIE 2019



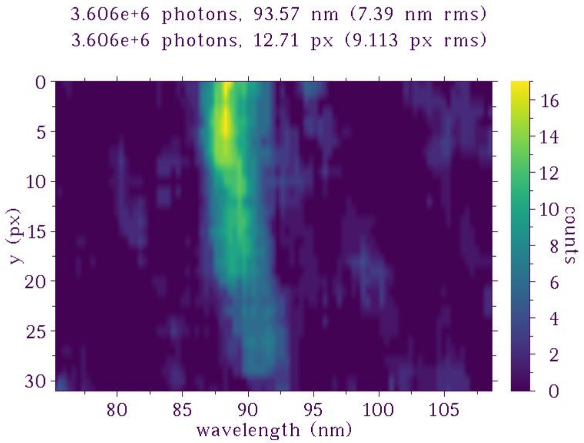
$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{a_u^2}{2} + \gamma^2\theta^2\right)$$





Beam transport to undulator

EuPRAXIA Programme: Explore attosecond FEL and synchrotron X-ray sources

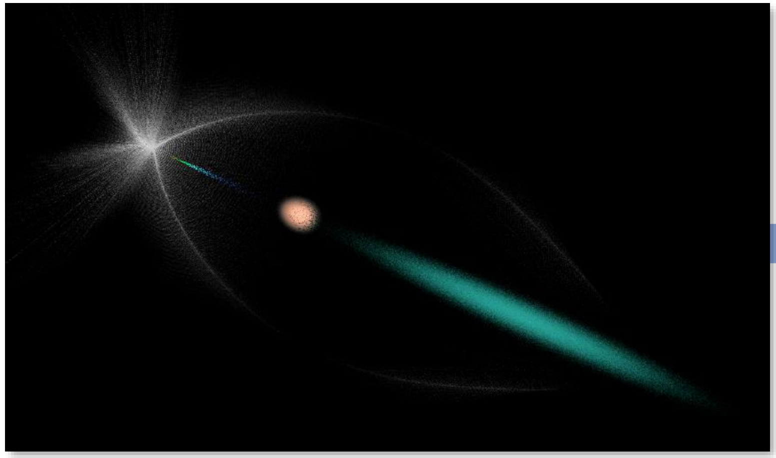


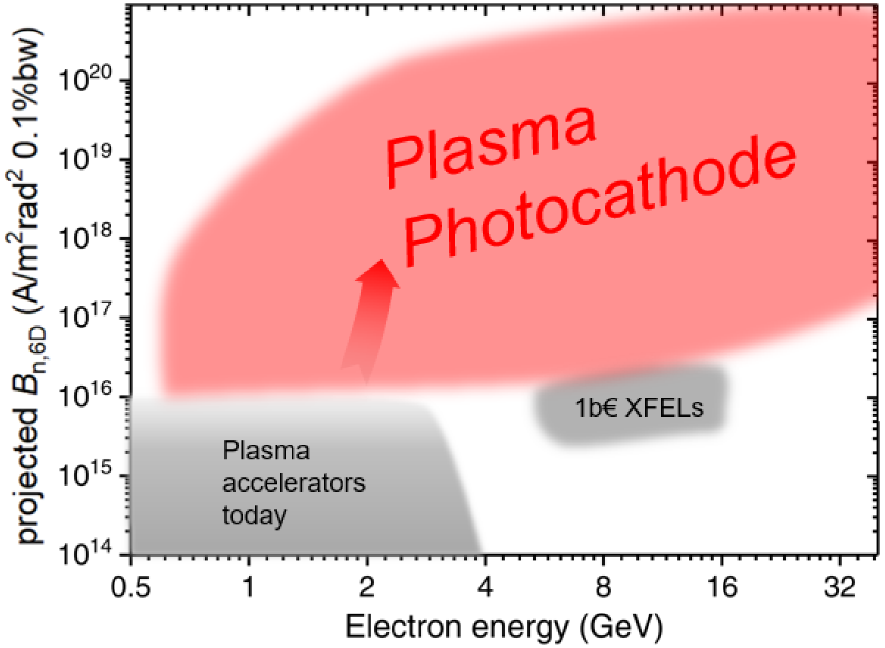
Peak brightness equivalent to a 3rd gen. synchrotron source but pulse duration 2-3 orders of magnitude shorter: **1-5 fs**

dino@phys.strath.ac.uk EuPRAXIA 2019

Plasma Photocathode: Trojan Horse-II

- The Plasma Photocathode is a unique path to ultralow (nm rad) normalized emittance, ultrahigh brightness electron beams (1000x better than state-of-art)
- Works as brightness booster stage for linacs as well as for LWFA
- Mechanism: release ultracold electrons via laser-based tunneling ionization in an electron-beam driven PWFA stage (Hidding et al., *PRL* 108, 035001, 2012)
- First demonstration in the "E-210: Trojan Horse" programme at SLAC FACET (Deng, Karger et al., *Nat. Phys.* 2019) in 90° geometry

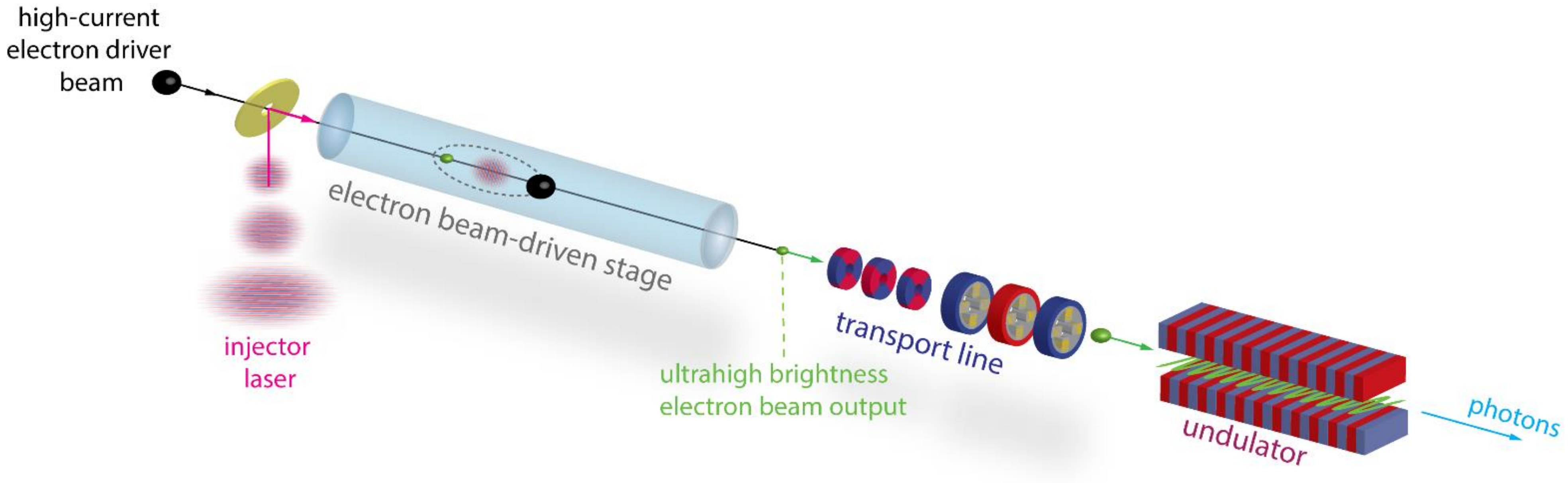




- Advanced version (Manahan, Habib et al., *Nat. Comm.* 8, 15705, 2017), featured as EuPRAXIA highlight, promises ultrahigh 6D- on top of ultrahigh 5D-brightness
- Next stop "E-310: Trojan Horse-II" at SLAC FACET-II in collinear geometry

Plasma Photocathode & PWFA-FEL

- Coordinated programme aiming to exploit ultrahigh brightness beams from a plasma photocathode for x-ray free-electron-lasers funded by UK‘s Science and Technology Facilities Council STFC 2019-2023
- UK-US collaboration: Strathclyde-ASTeC-SLAC-UCLA on “Exploratory Stuy of PWFA-driven FEL at CLARA“
- Approach: Plasma photocatode-level electron beams will exceed X-FEL lasing thresholds by wide margin
- Ultrahigh FEL gain, potentially sub-attosecond pulses possible: designer electron and photon beams



- Experimental programmes at linac-based facilities SLAC FACET(-II) in the E-31x experiments, Daresbury Lab CLARA initiated, hopefully at DESY & INFN and elsewhere

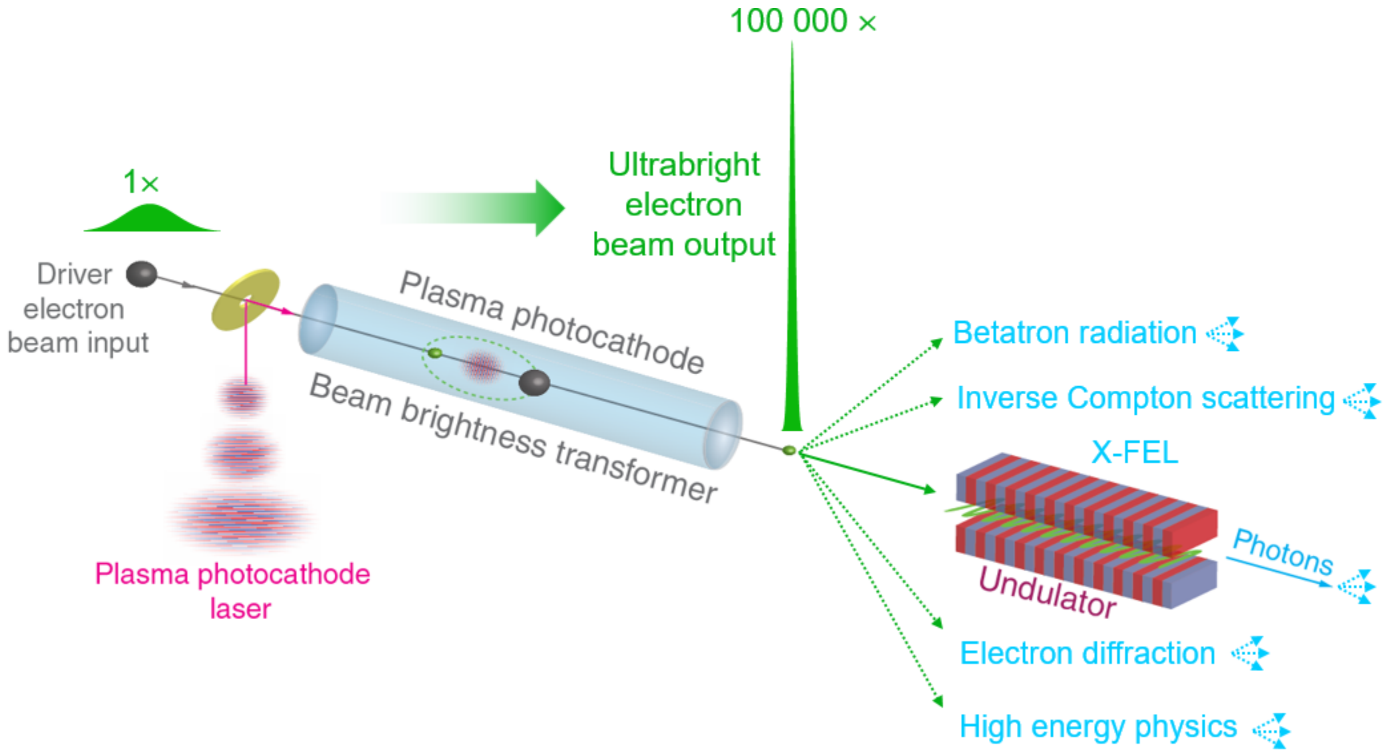
Hybrid LWFA → PWFA → Plasma Photocathode

Horizon 2020

Hidding
University of Strathclyde Glasgow

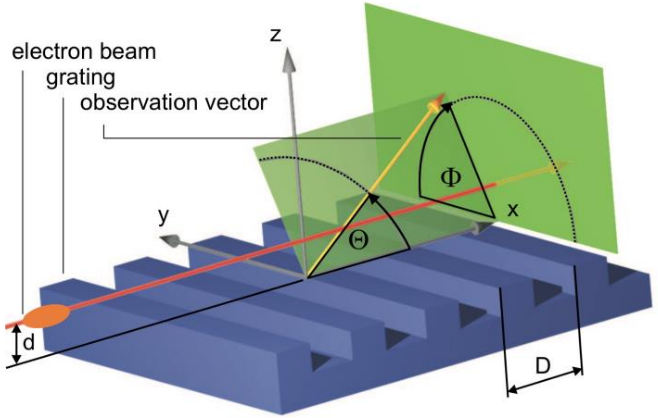
- Concept: LWFA produces near-ideal electron beams to drive PWFA (EuPRAXIA WP 14, Hidding & de la Ossa; (Hidding et al., PRL 104, 195002, 2010)
- First experimental attempts have been made in the US DOE "Plasma Photocathode Beam Brightness Transformer for Laser-Plasma Accelerators" project, which led e.g. to linac-driven proof-of-concept of the plasma photocathode (Deng, Karger et al., *Nat. Phys*. 2019)
- Hybrid approach may profit from inherent synchronization between drive beam and plasma photocathode laser

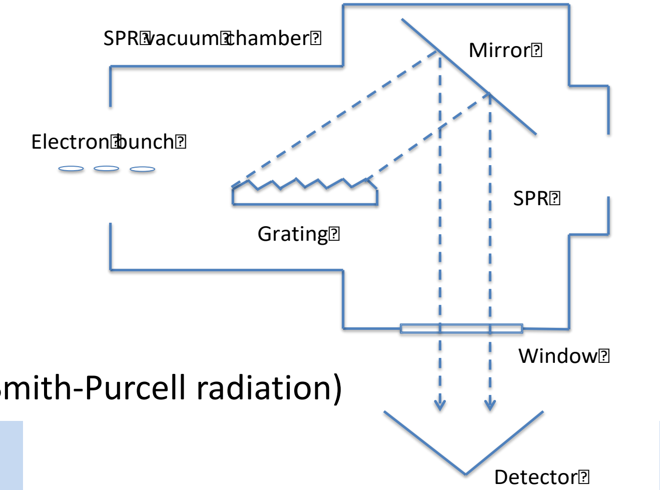
- Hybrid Collaboration Strathclyde-DESY-HZDR-LMU-LOA explores this path with experiments at HZDR, LMU, LOA: Gilljohann et al., *PRX* 9, 011046, 2019; Kurz, Heinemann et al., under review
- In the UK, this and further (e.g. high rep-rate) approaches are coordinated by the Plasma Wakefield Accelerator Steering Committee and its Roadmap
- The Scottish Centre for the **Application** of Plasma-based Accelerators (SCAPA) and the Extreme Photonics **Applications** Centre (EPAC) at CLF provide Euro-friendly infrastructures to develop this path



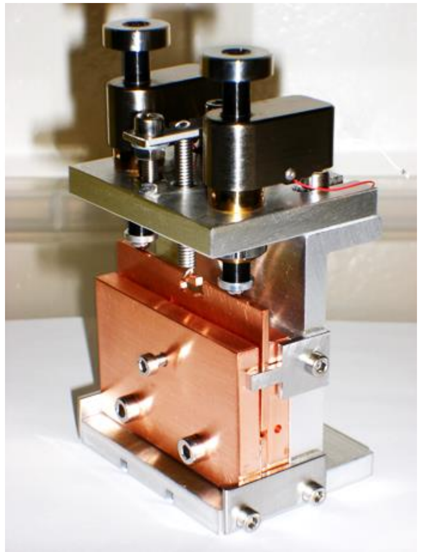
THz radiation source at EuPRAXIA

- Two methods to generate high power coherent THz radiation at EuPRAXIA
- One is based on Smith-Purcell Radiation (SPR via metallic gratings)
- The other is based on beam driven dielectric structures (diamond, quartz, silica…)
- Big advantages to use EuPRAXIA beam as drive beam, i.e. high energy (~GeVs), ultrashort bunch length (fs), ultralow emittance (µm), decent charge (10s to 100s pC)





(Smith-Purcell radiation)



THz source

- 2 mm wide
- 40 mm dielectric length
- 25 um thick quartz

(THz source in dielectric structures)

Courtesy to T. Pacey (Manchester Uni/STFC)

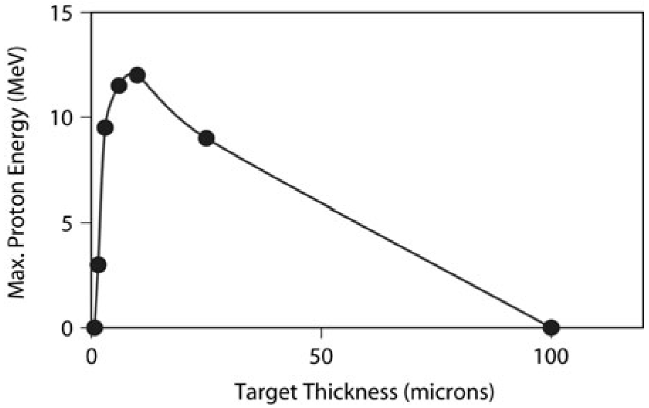
The TARANIS ps-scale laser at QUB

Horizon 2020

- TARANIS: dual-beam high-power laser hosted by the Centre for Plasma Physics at Queen's University Belfast

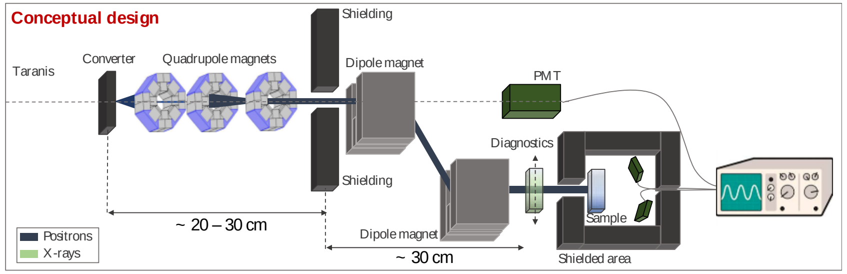
	TARANIS (compressed)	TARANIS (stretched)
Wavelength	1053 nm	1053 nm
Pulse duration	600 fs	1.2 ns
Energy on target	15 J	25 J
Max. Intensity	$2x10^{19}$ Wcm^{-2}	$2x10^{16}$ Wcm^{-2}
Rep. rate	1 shot / 10 minutes	1 shot / 10 minutes

- Proton acceleration



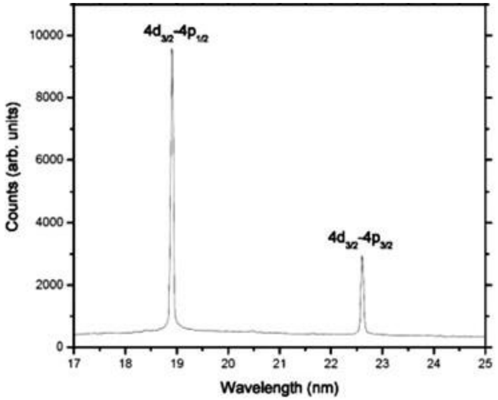
Up to 12 MeV high-flux ps-scale proton beams

- Low-energy positrons *(data being analysed)*



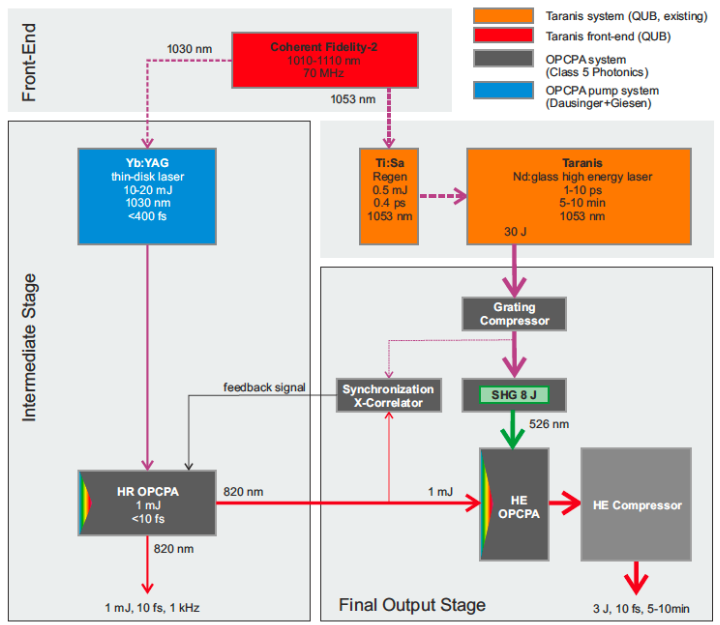
- *Energy tuneable from 0 to 3 MeV*
- *20 – 30 ps duration per energy slice*
- *Up to 4 pC per shot*
- *Ideal for material inspection (PALS)*

- hard X-rays



T. Dzelzainis et al., Laser and Particle Beams (2010), 28, 451

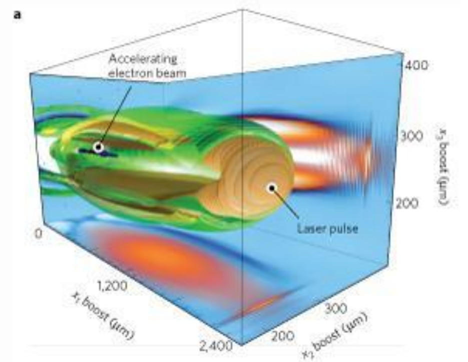
The TARANIS-X fs upgrade at QUB



- TARANIS-X: femtosecond high-power laser hosted by the Centre for Plasma Physics at Queen's University Belfast

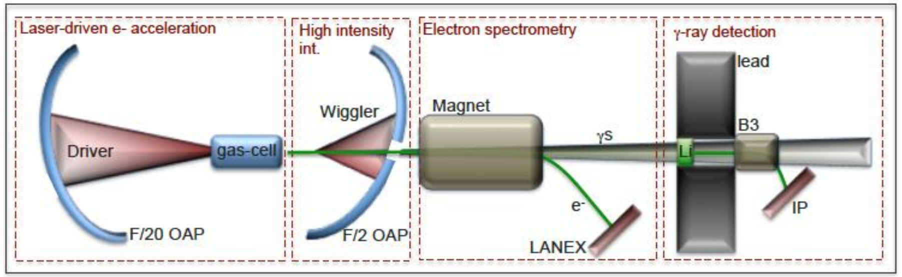
	TARANIS-X (low-energy mode)	TARANIS-X (high-energy mode)
Wavelength	820 nm	820 nm
Pulse duration	10 fs	10 fs
Energy on target	0.3 mJ	1 J
Max. Intensity	3×10^{16} Wcm^{-2}	10^{20} Wcm^{-2}
Rep. rate	1 kHz	1 shot / 5 minutes

Electron acceleration



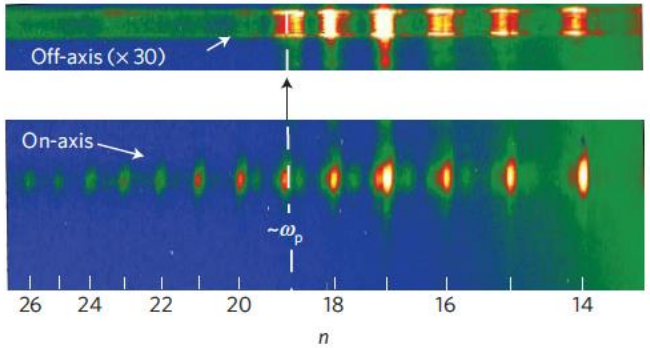
- *Long focal length setup (F/13)*
- *First experiments in Autumn 2020*

Thomson scattering



- *Combined F/3 + F/13 setup*
- *First experiments beginning 2021*
- *Tuneable MeV high-flux source of gamma rays*

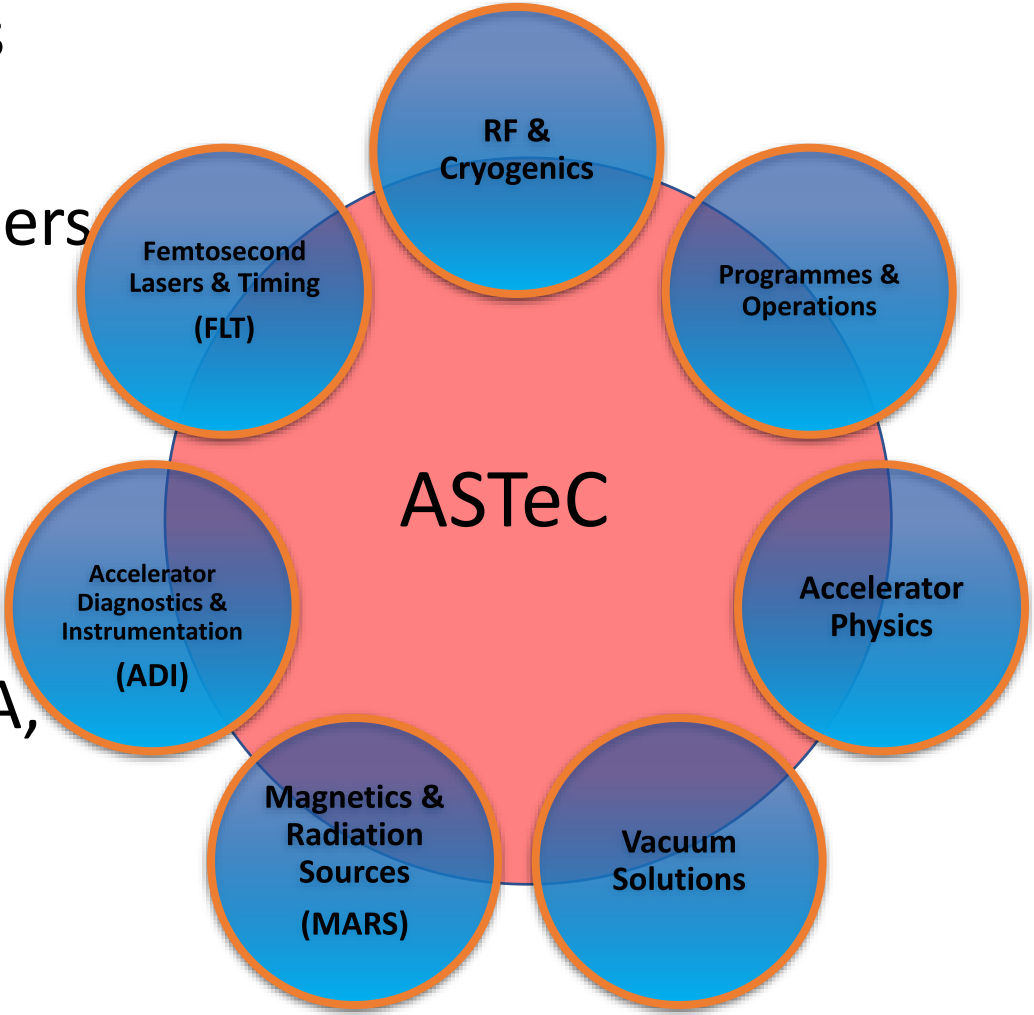
High-harmonics



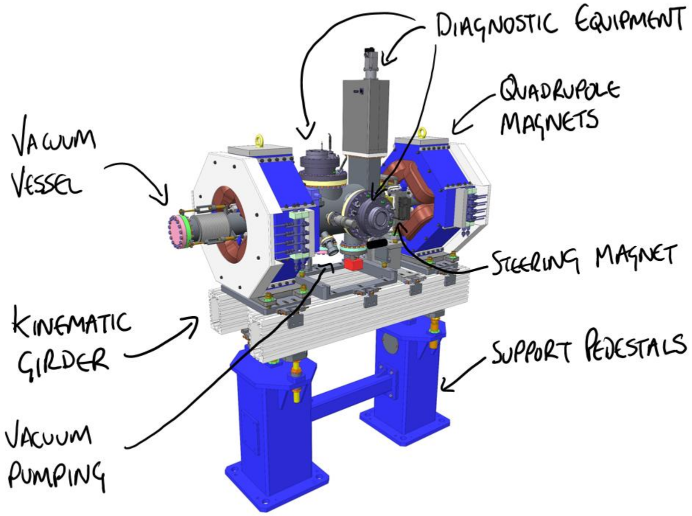
- *kHz operation at mJ level*
- *fs and sub-fs harmonics from gas targets*
- *First exeriments in Summer 2020*

Accelerator Science & Technology Centre

- ASTeC is STFC's accelerator department and it is based at Daresbury Laboratory
- ~75 professional accelerator scientists & engineers
- Supported directly by ~100 engineers from Technology Department across STFC
- ASTeC has a proven track record of designing, building, and delivering innovative accelerators
- Recent examples at Daresbury are ALICE, EMMA, VELA, and now CLARA



- ASTeC also has a proven track record of delivering major accelerator systems to leading international facilities overseas
- Current major examples include HL-LHC, ELI-NP, ESS, SwissFEL, and PIP-II

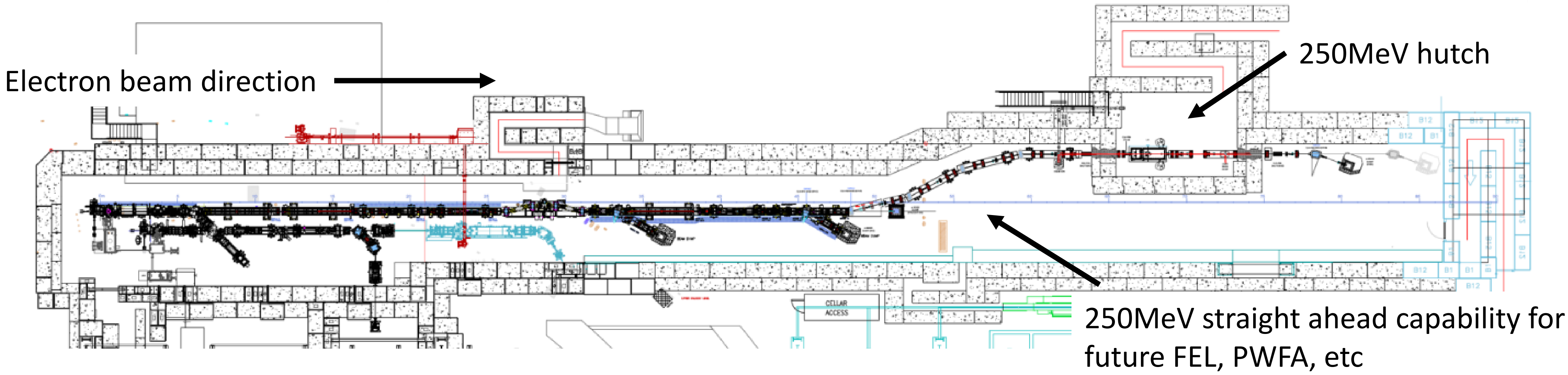



Accelerator module M7 being offloaded at IFIN-HH

STFC is supplying 70% of the ESS vacuum beamline, including the linac warm units, shown here prior to delivery in July 2019

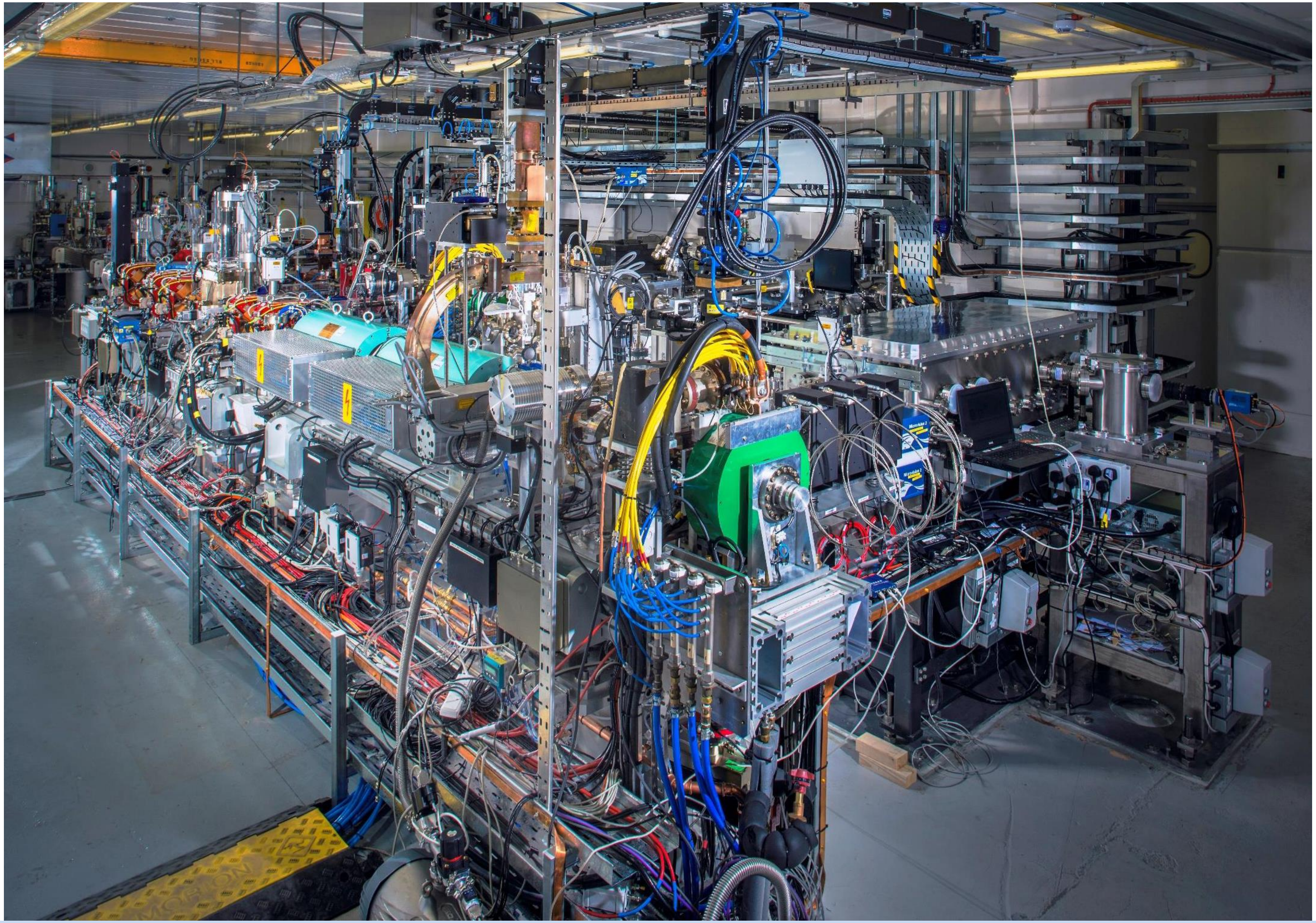
CLARA

- CLARA is STFC's flagship accelerator test facility designed to operate at 400 Hz
- Currently operational at up to 50MeV, and planned to reach 250MeV in 2022
- CLARA generates very bright, femtosecond electron beams of FEL quality
- A dedicated beamline and experimental hutch will be available for open access, enabling PWFA experiments

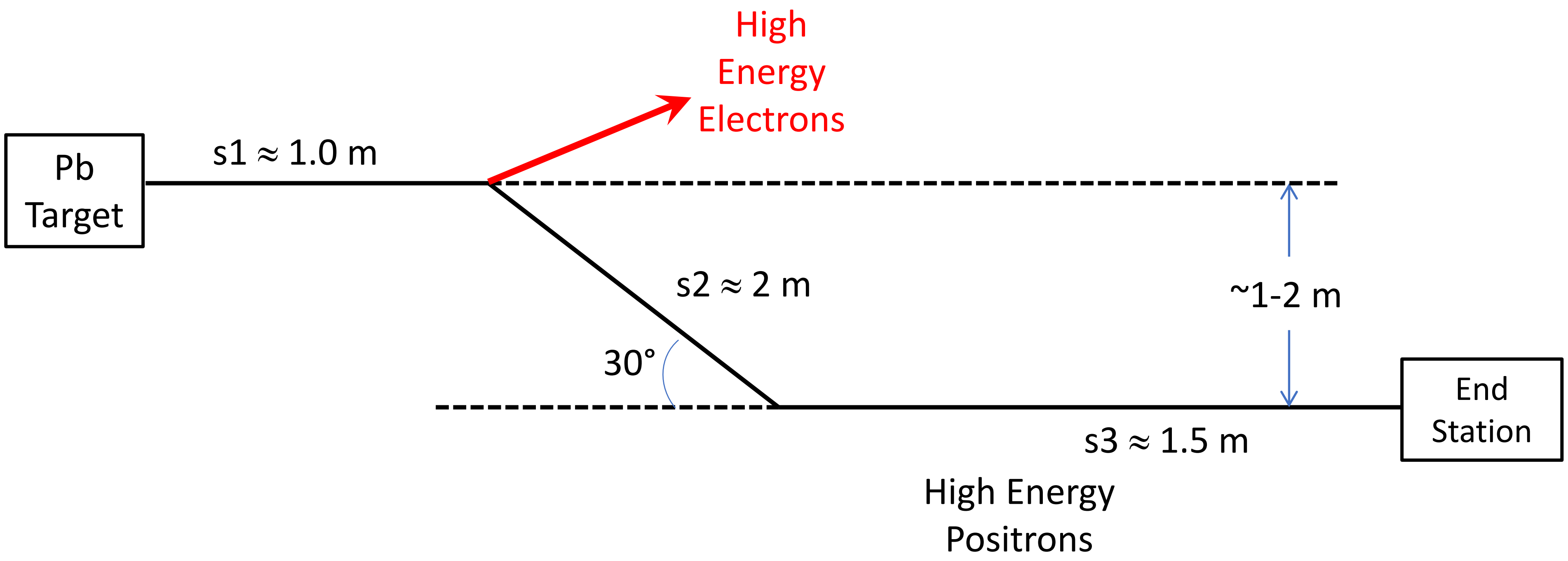


CLARA

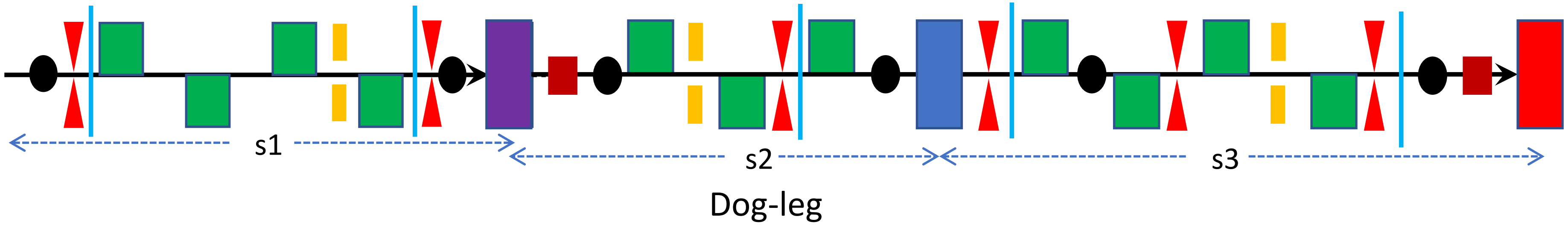
CLARA Phase 1 is operational and delivering bright 100 pC, 50MeV electron bunches to users for a variety of experiments



EuPRAXIA High Energy Positron Beamline Concept



EuPRAXIA High Energy Positron Beamline Concept



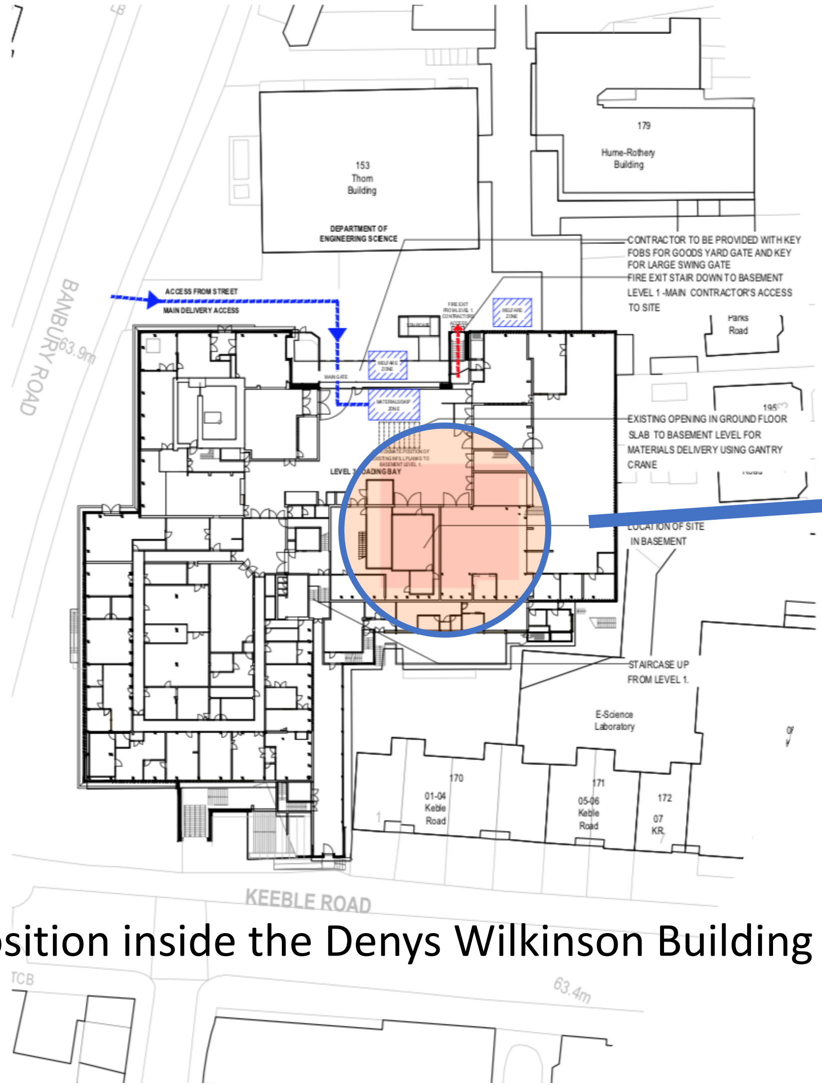
- – YAG screens
- – charge measurement
- – vacuum pump & gauge
- – correctors (H & V)
- – collimators / apertures
- – separator dipoles

New Laboratory for Laser Wakefield Acceleration and Lab Astrophysics

Department of Physics, Denys Wilkinson Building

- Currently under construction in basement of Denys Wilkinson Building, Oxford
- Joint use by Gianluca Gregori (lab astrophysics & warm dense matter) and Simon Hooker (laser wakefield acceleration)
- Hooker group: Installing new multipass amplifier, adaptive optic etc. from Amplitude Technologies on top of an existing front-end
- 600 mJ / 40 fs on target – similar to Astra at CLF, Rutherford Appleton Laboratory – where experiments on multiple pulse laser wakefield acceleration and long channels have been performed

Plans for new laboratory

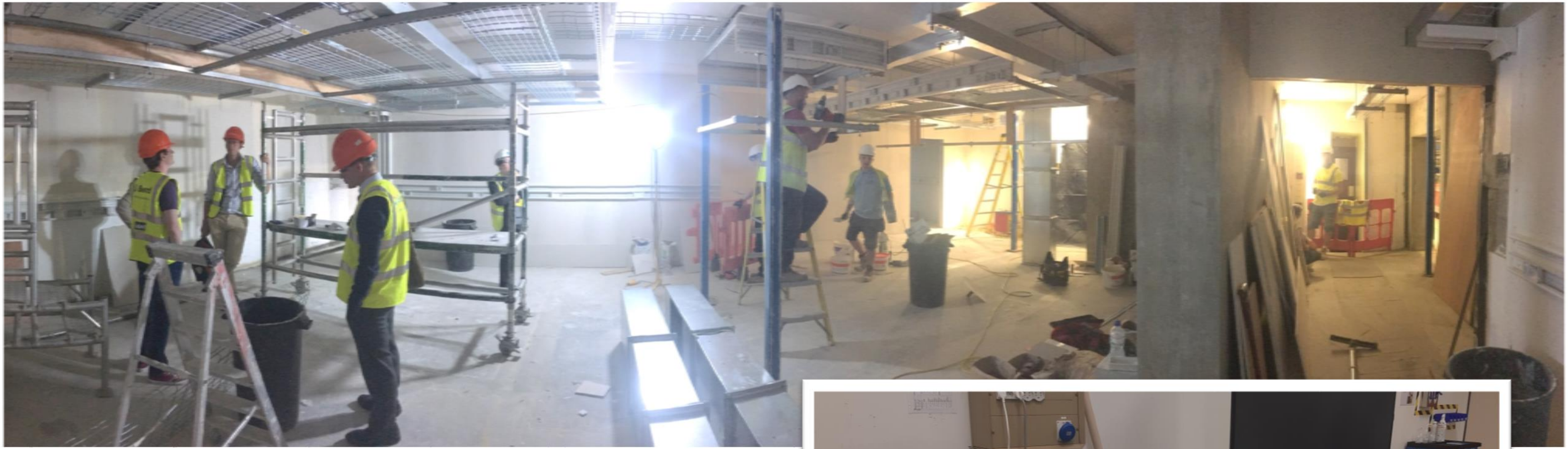


Current position inside the Denys Wilkinson Building basement

Layout of the new laboratories

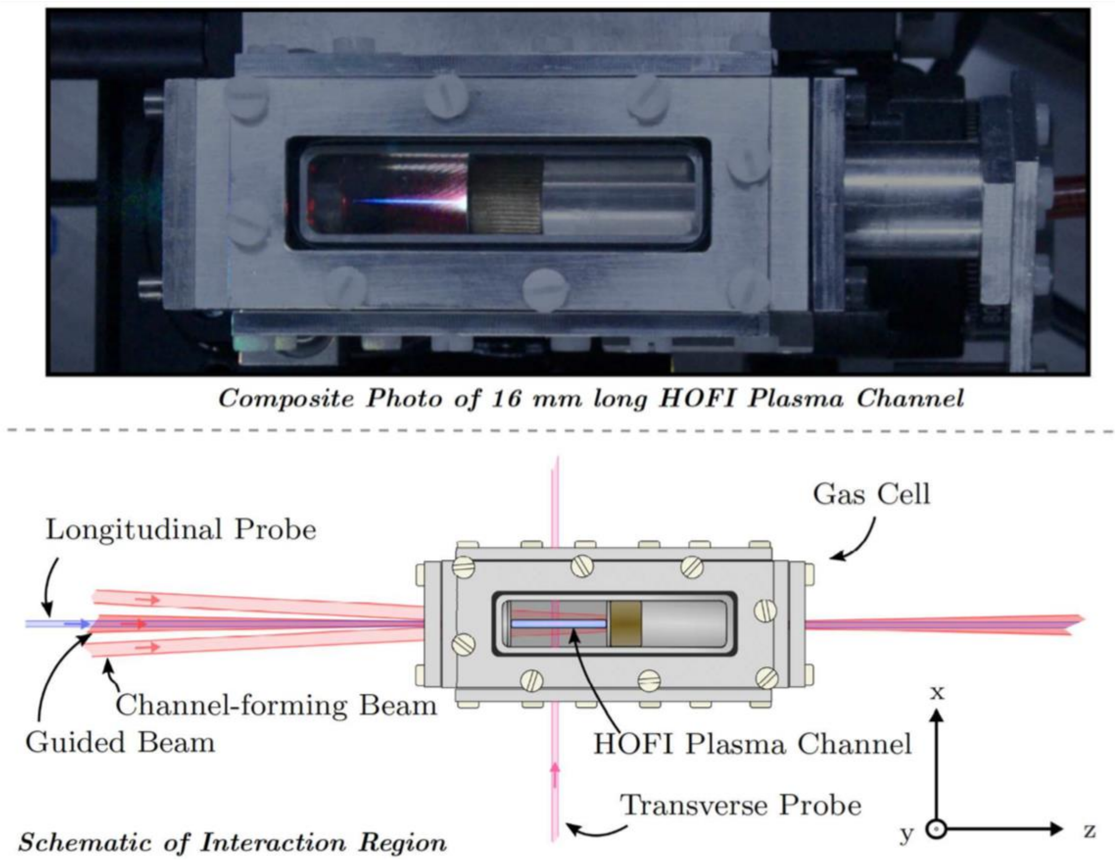
1. Laser room; 2. Gregori group target area; 3. Hooker group target area

Current status



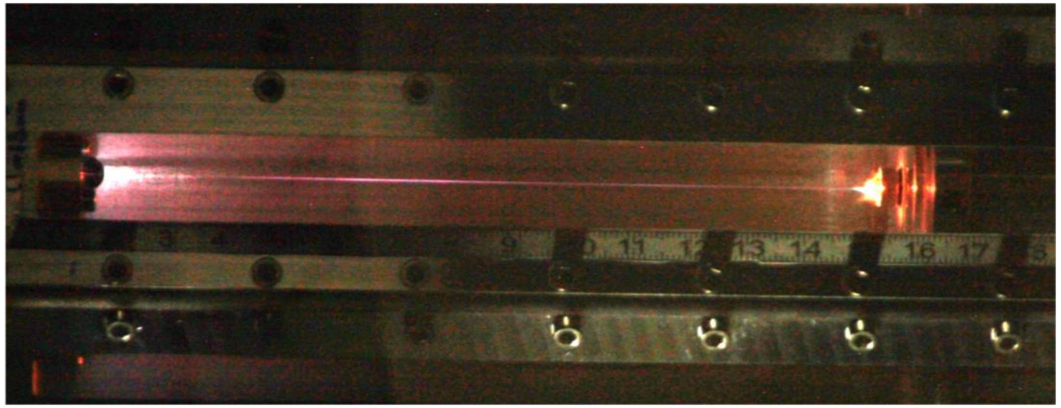
- Demolition work began in June.
- Current status as per picture!
- Due to be completed mid-October
- Amplitude Technologies are commissioning the new multipass – much more compact than Astra!

Continuation of HOFI channels



16 mm plasma formed using Astra laser

Preliminary! 15 cm plasma formed using Gemini laser

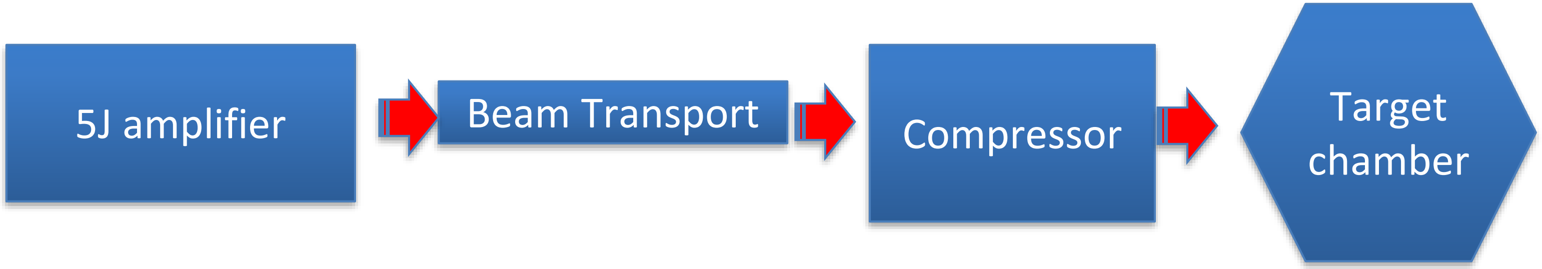


- 16 mm long hydrodynamic optical-field-ionized plasma channels for guiding were made at Astra – published 2018

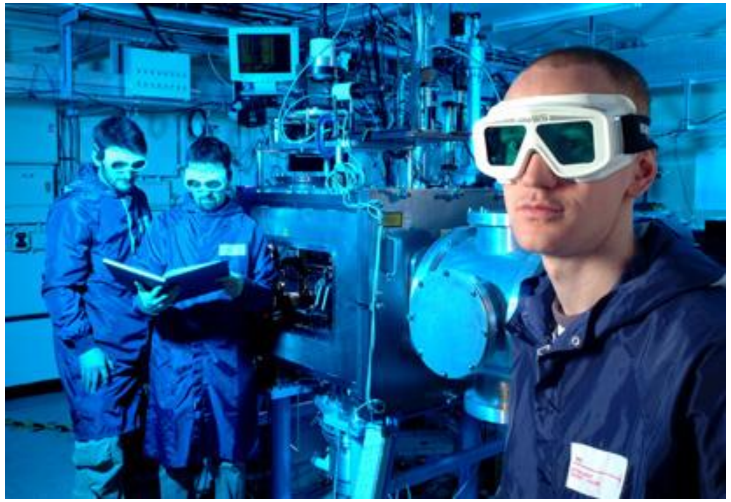
R. J. Shalloo, C. Arran, L. Corner, J. Holloway, J. Jonnerby, R. Walczak, H. M. Milchberg, and S. M. Hooker Phys. Rev. E ***97****, 053203* 7 May 2018

- Work recently extended to > 10 cm plasma and guiding over several cm at Gemini – see Alex Picksley's poster!
- Intention to use new lab to continue this research

Eupraxia prototyping for HOPA



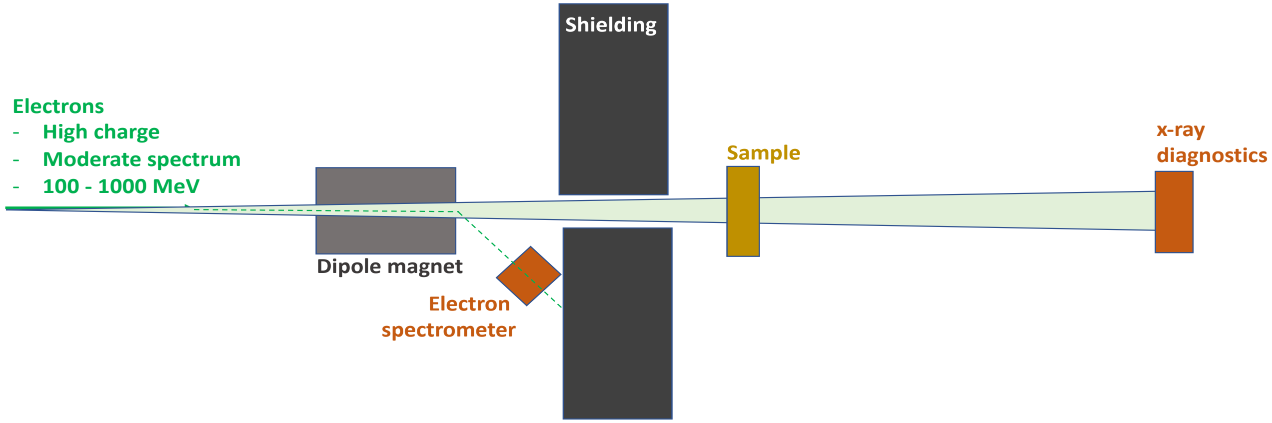
- Proposing to upgrade Astra (Gemini front-end) to 100 TW @10Hz (currently 15 TW)
- Dedicated beamline for LWFA
- Ideal test ground for most of these tests
- Expertise in “facility mode” operations : engineering design, radiation handling, high volume data analysis, diagnostics



Eupraxia prototyping for HOPA

- 10Hz betatron/Compton/Bremsstrahlung source with 100 TW

Betatron beamline

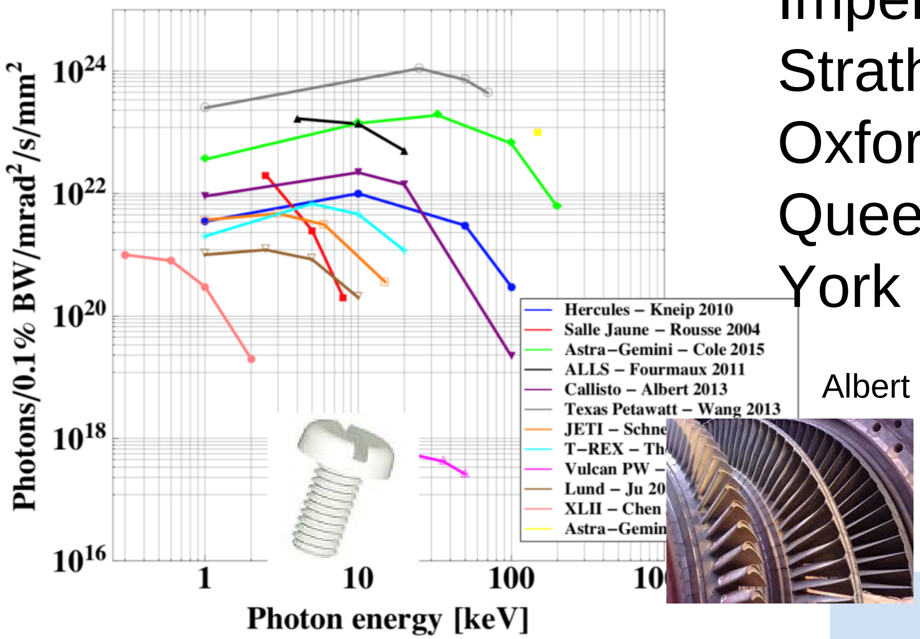


Critical Energy
25 +/- 5 keV

Estimated source size ($2r_\beta$)
1.0 µm

Number of photons per shot
$(7 \pm 3) \times 10^9$

Brightness (30 fs pulse)
$(1.0 \pm 0.4) \times 10^{24}$
photons/s/mrad²/mm²/0.1% BW.

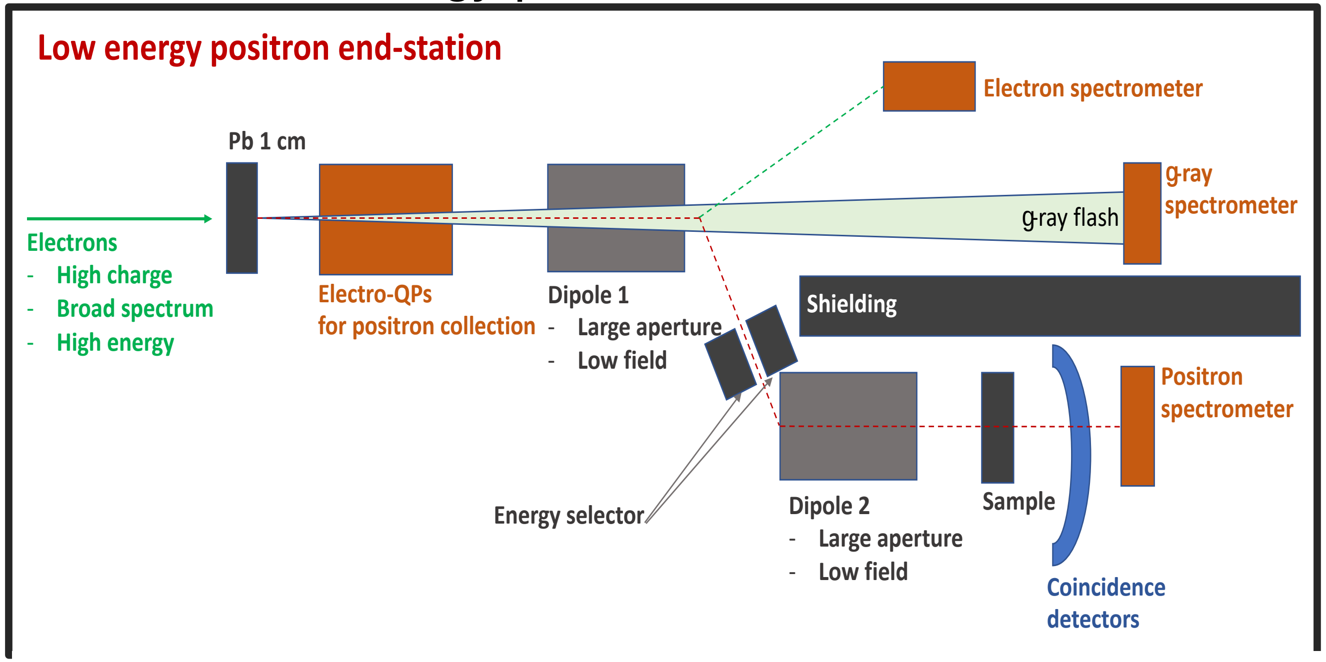


Imperial,
Strathclyde,
Oxford,
Queens,
York

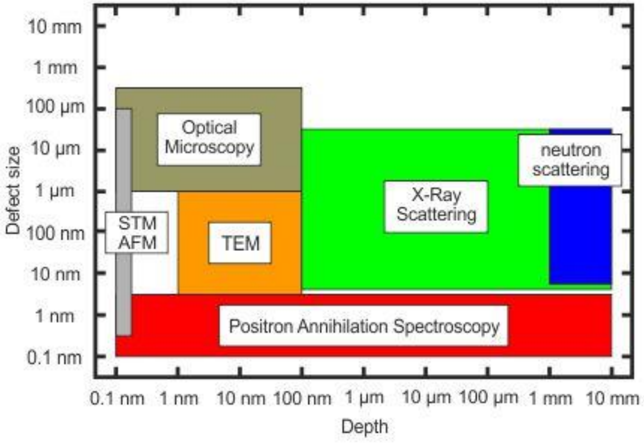
Albert and Thomas

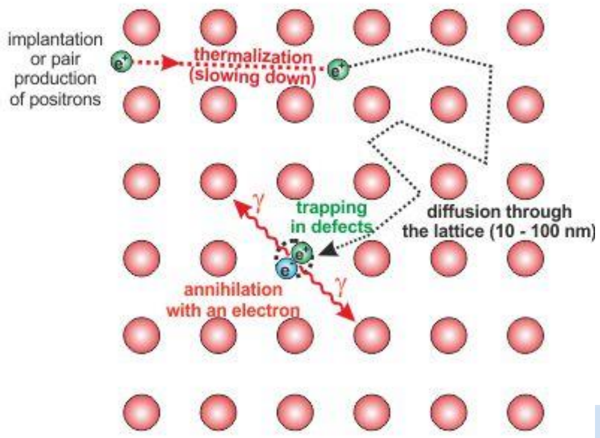
Eupraxia prototyping for HOPA

- 10Hz low-energy positron beams



Imperial,
Strathclyde,
Oxford,
Queens,
York
ASTeC





Positron Annihilation Lifetime Spectroscopy

7 slides have been removed

- 7 slides have been removed

EuPRAXIA Excellence Centre for Advanced Applications Beamlines in the UK

- For some years UK research has been strongly oriented towards the development of applications. The UK funding councils are operated through the UK's department for Business, Energy, Industrial Strategy (BEIS), and several of the funding streams they control are aligned with industrial applications.
- The EuPRAXIA consortium has identified the following pilot applications: Free Electron Laser (FEL), high-energy (GeV) and low-energy (sub-MeV) positron beamlines, a Compton source of MeV gamma-ray beams, and betatron x-ray sources. Several other applications can be envisaged, but these end-stations are the ones that allow pursuing specific electron beam parameters that are thought to accommodate the widest range of future applications.
- Current plans and investments in the UK are very well aligned with EuPRAXIA plans documented in the EuPRAXIA CDR. We propose that EuPRAXIA Excellence Centre for Advanced Applications Beamlines is located in the UK. And that the UK builds prototypes, develops all beamlines, and plays a major role in their delivery.