Electron plasma acceleration
and
the EuPRAXIA project

Roman Walczak
John Adams Institute & Department of Physics, University of Oxford, UK

Outline

- Brief history

UK
  - Last year Highlights →
  - Good News
  - ~~Plans~~ →
  - ~~Facilities/lasers~~
- EuPRAXIA
- Summary

- laser driven
  - accelerating structure and laser pulse guiding
  - electron injection
  - radiation
  - diagnostics
  - electron beam optics
  - theory
  - other
- electron driven
- proton driven

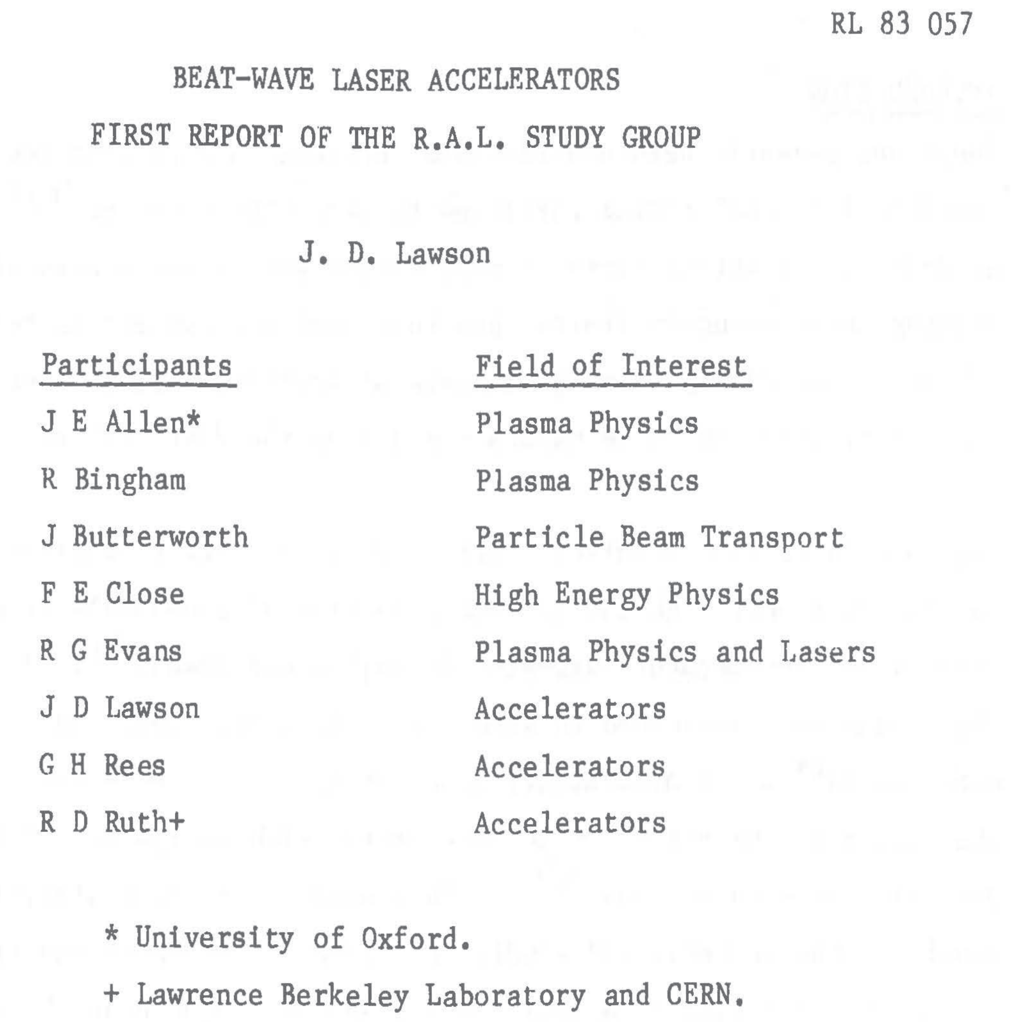
History

- T. Tajima and J.M. Dawson, Laser Electron Accelerator, PRL Vol. 43, 267 (July 1979)

- One very high intensity (short) laser pulse

OR

- two not so short high energy pulses with the beat frequency matching plasma frequency.



RL 83 057

BEAT-WAVE LASER ACCELERATORS

FIRST REPORT OF THE R.A.L. STUDY GROUP

J. D. Lawson

Participants	Field of Interest
J E Allen*	Plasma Physics
R Bingham	Plasma Physics
J Butterworth	Particle Beam Transport
F E Close	High Energy Physics
R G Evans	Plasma Physics and Lasers
J D Lawson	Accelerators
G H Rees	Accelerators
R D Ruth+	Accelerators

* University of Oxford.

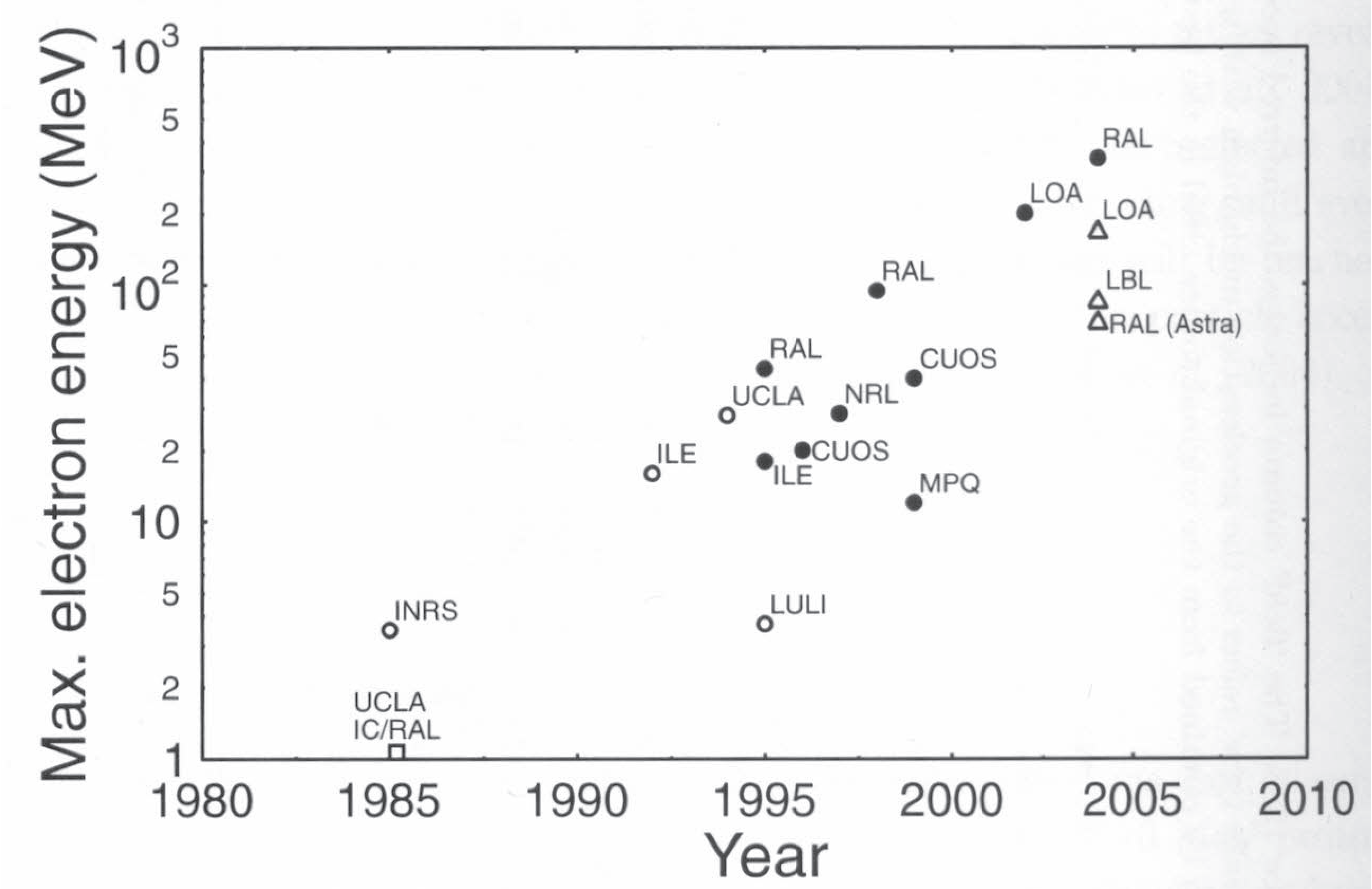
\+ Lawrence Berkeley Laboratory and CERN.

From the Abstract:
An attempt is being made to see what is involved in constructing a high energy accelerator using laser beat-wave principle...

High energy means here TeV level

Please note participants' fields of interest

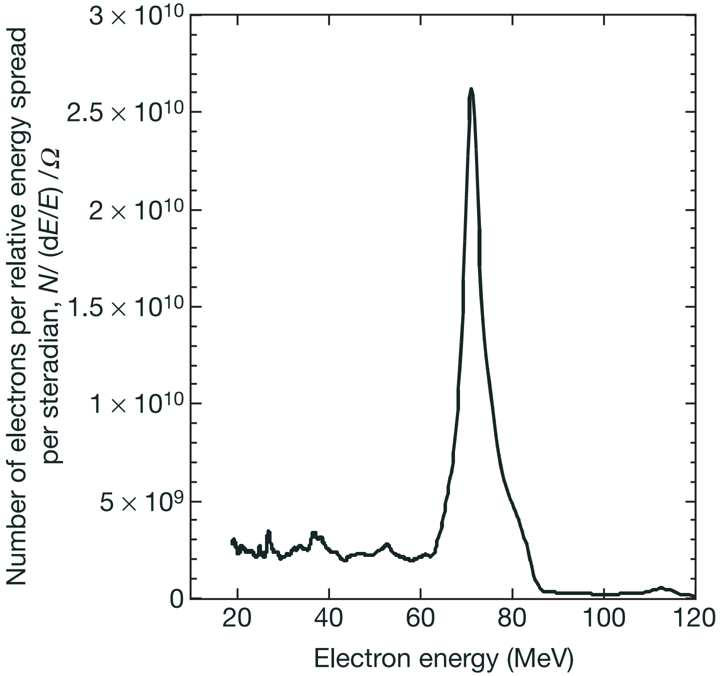
History



credit: P. Gibbon “Short Pulse Laser Interactions with Matter”, ICP 2005

History

The breakthrough



2004

Monochromatic beam

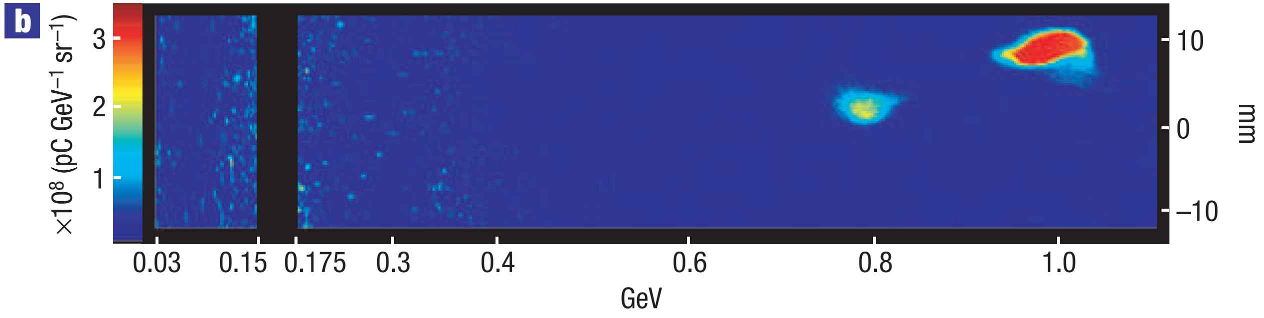
CLF, IC, Strathclyde, UCLA.

S.P.D. Mangles et al., Nature 431, 535-538 (2004)

and

J. Faure et al. , Nature 431, 541-544, (2004)

C.G.R. Geddes et al., Nature 431, 538-541 (2004)



2006

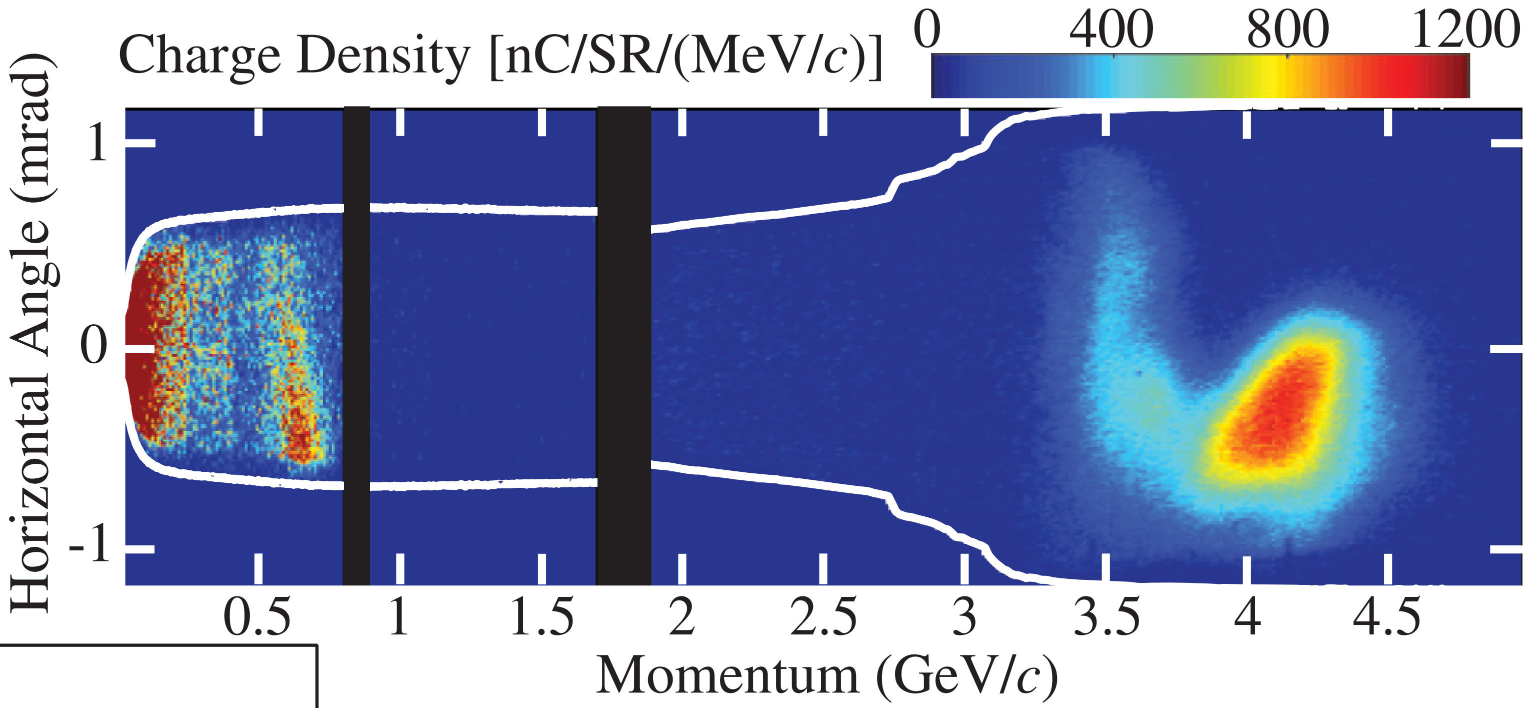
GeV beam

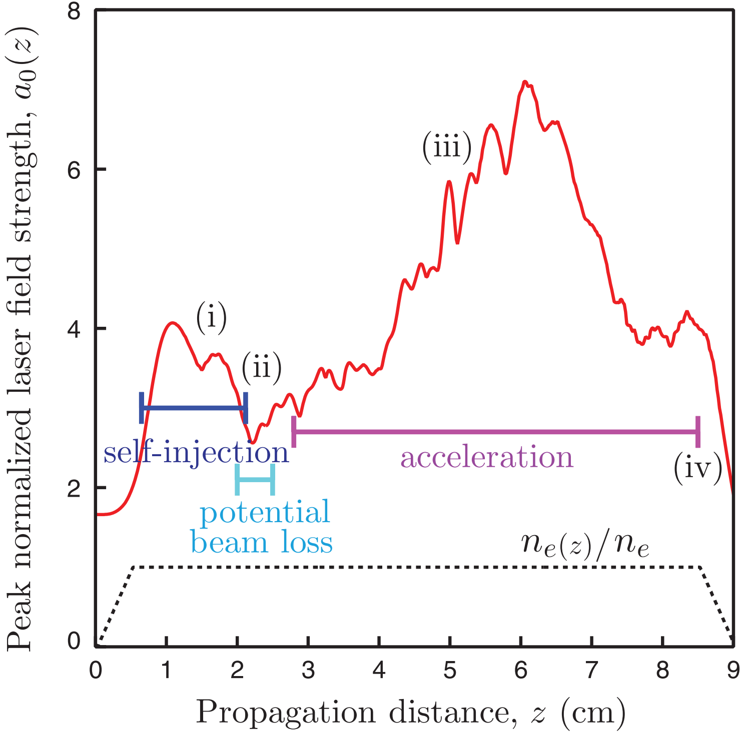
LBNL, Oxford, Tokyo.

W.P. Leemans et al.,

Nat.Phys. 2, 696 (2006)

History





2014
4.2 GeV beam

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

Emerging directions

Emerging main directions:

In the US

- a roadmap to high energy colliders; TeV energies

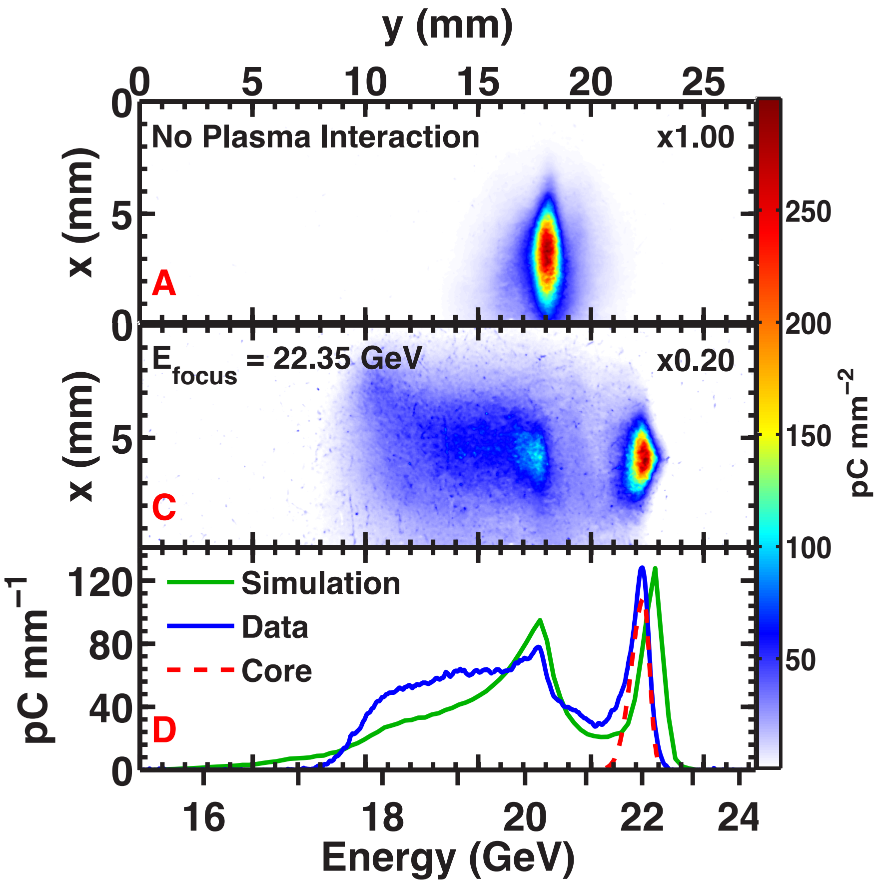
In Europe

- a roadmap to light sources; GeV energies

All agree

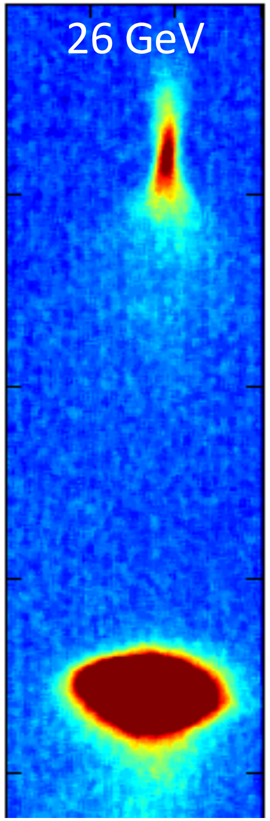
- more efficient, higher repetition rate lasers are needed

FACET two-bunch results



- *1.7 GeV* energy gain in *30 cm* of Li vapour plasma.
- 2% energy spread.
- Accelerated bunch has charge ~ *70 pC*
- Up to *30%* wake-to-bunch energy transfer efficiency (mean *18%*).
- *6 GeV* energy gain in *1.3 m* of plasma.

1.3 m plasma



2014

M. Litos et al., Nature **515** (2014) 92

credit: M. Wing, Physics at the Terascale 2015

Proton Drivers for PWFA

Proton bunches as drivers of plasma wakefields are interesting because of the very large energy content of the proton bunches.

Drivers:

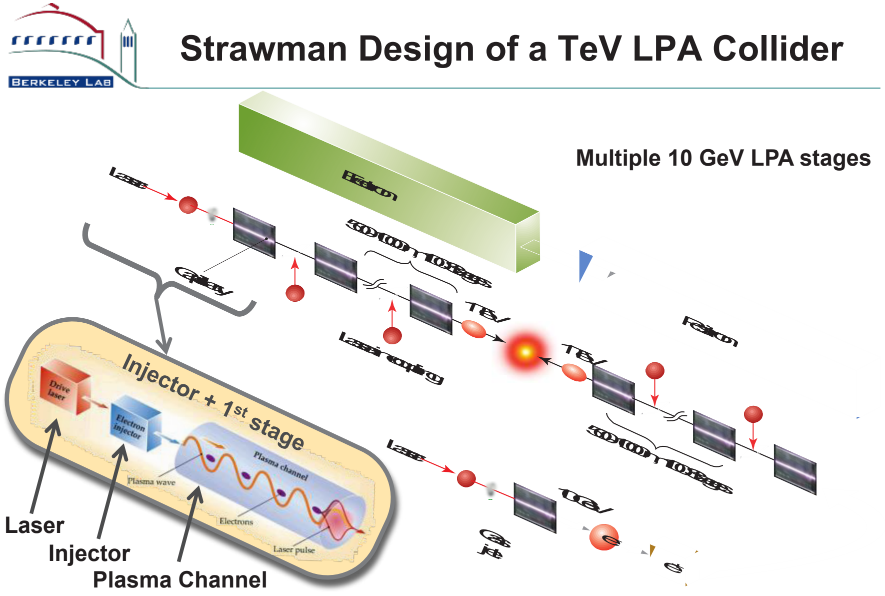
PW lasers today, ~40 J/Pulse

FACET, 30J/bunch

SPS 20kJ/bunch
LHC 300 kJ/bunch

Witness:

10^{10} particles @ 1 TeV ≈ few kJ



Leemans & Esarey, Physics Today, March 2009

Energy content of driver allows to consider single stage acceleration

credit: A. Caldwell, SPSC Meeting 2015

AWAKE

AWAKE Collaboration: 16 Institutes world-wide:

John Adams Institute for Accelerator Science,
Budker Institute of Nuclear Physics &
Novosibirsk State University
CERN
Cockroft Institute
DESY
Heinrich Heine University, Düsseldorf
Instituto Superior Tecnico
Imperial College
Ludwig Maximilian University
Max Planck Institute for Physics
Max Planck Institute for Plasma Physics
Rutherford Appleton Laboratory
TRIUMF
University College London
University of Oslo
University of Strathclyde

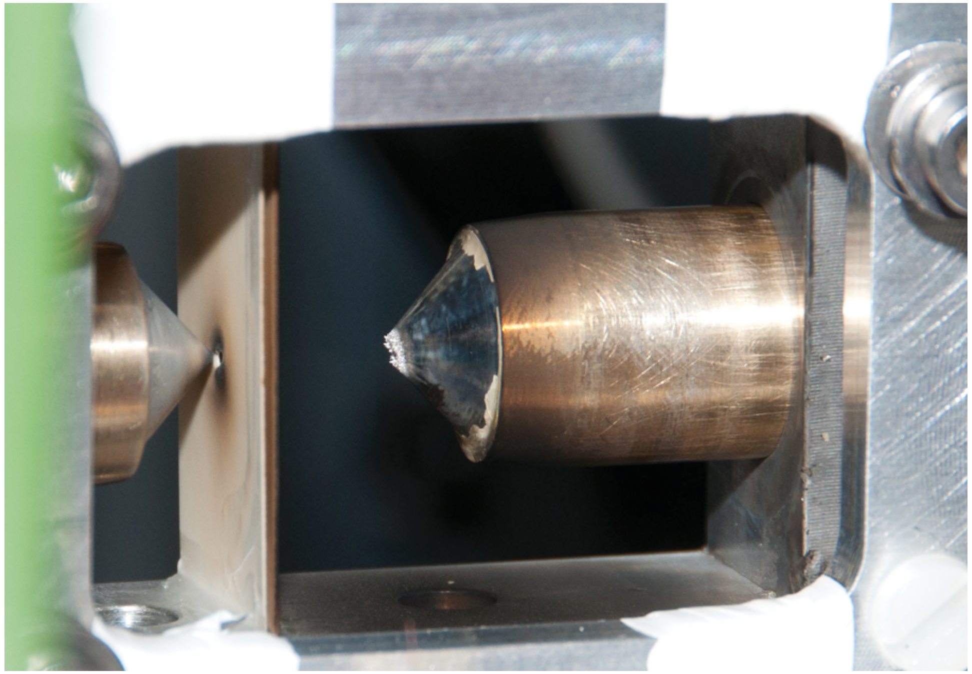
Requests under consideration:
Ulsan National Institute of Science and Technology (UNIST), Korea
Wigner Institute, Budapest
Swiss Plasma Center group of EPFL

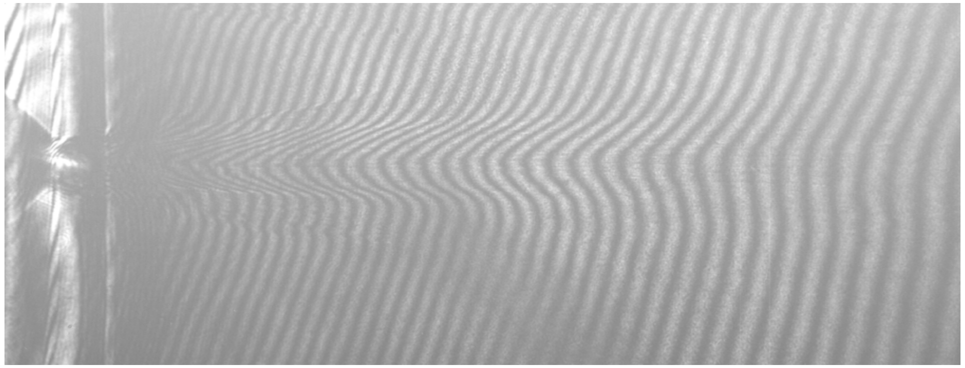
Further groups have also expressed their interest to join AWAKE.

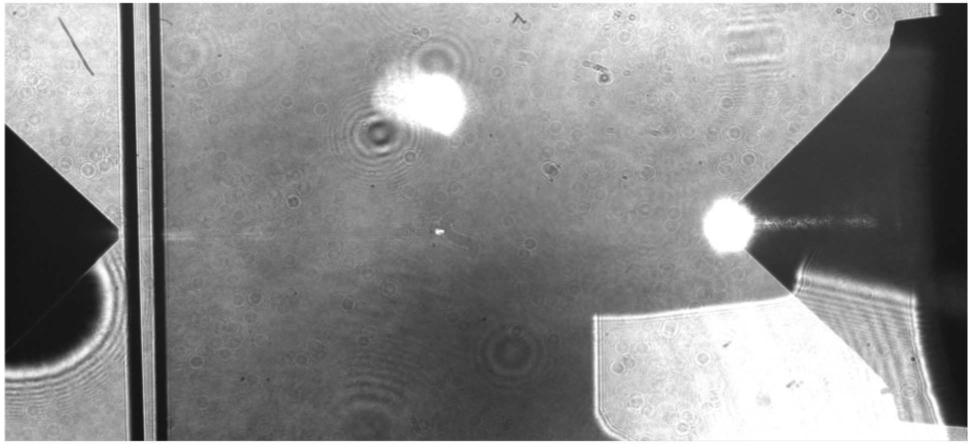
New since 2014 SPSC report

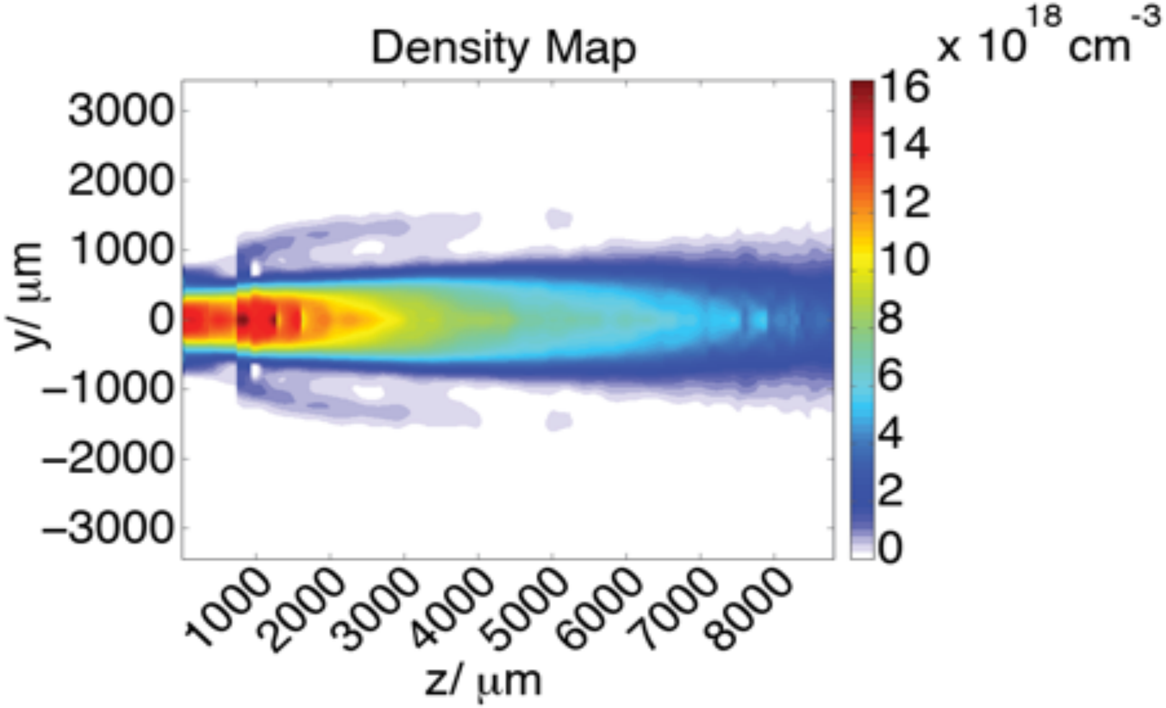
credit: A. Caldwell, SPSC Meeting 2015

Accelerating and guiding





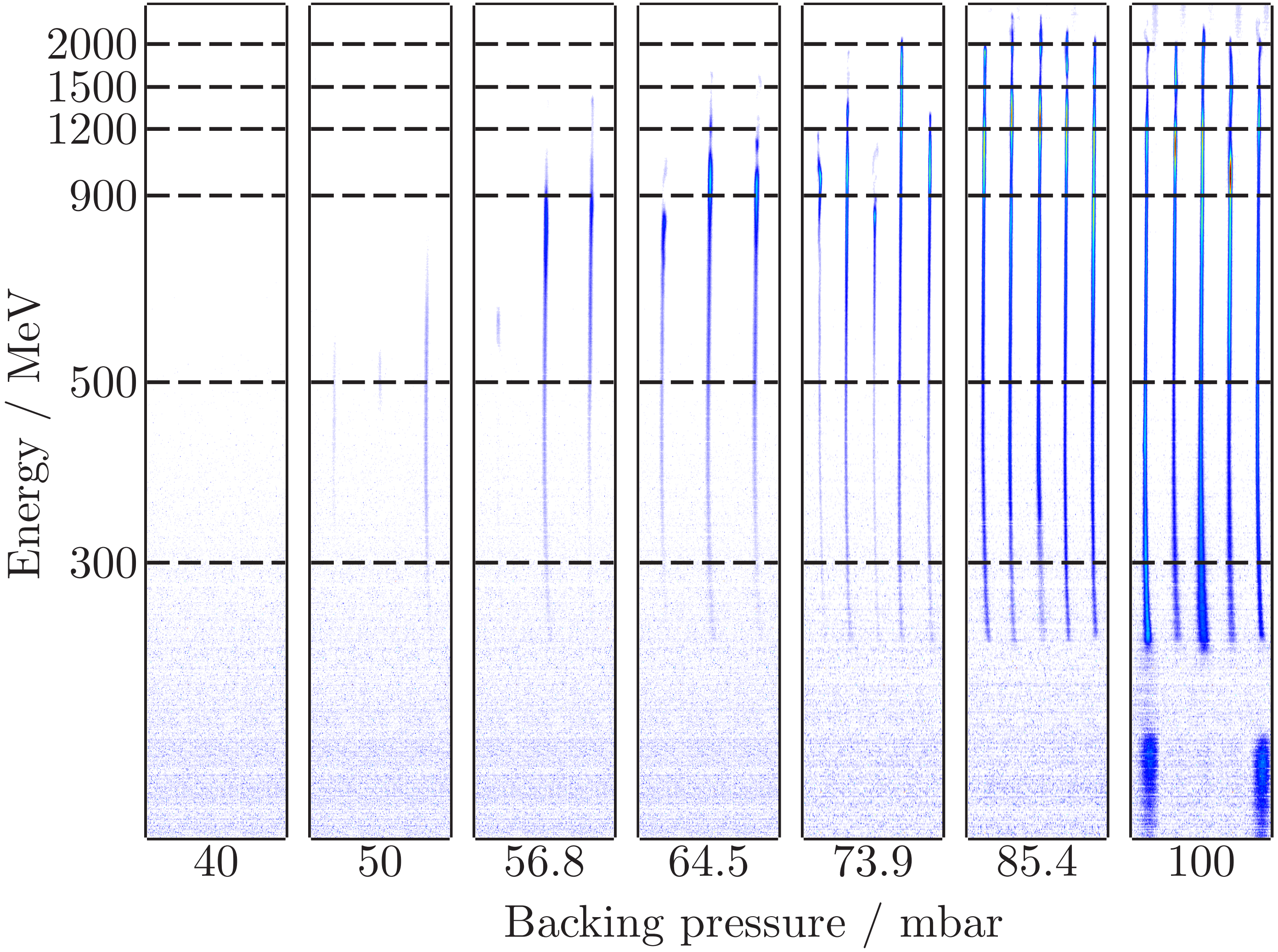




IC at CLF's GEMINI; 2015

credit: Z. Najmudin

Extended electron energies for same laser energy

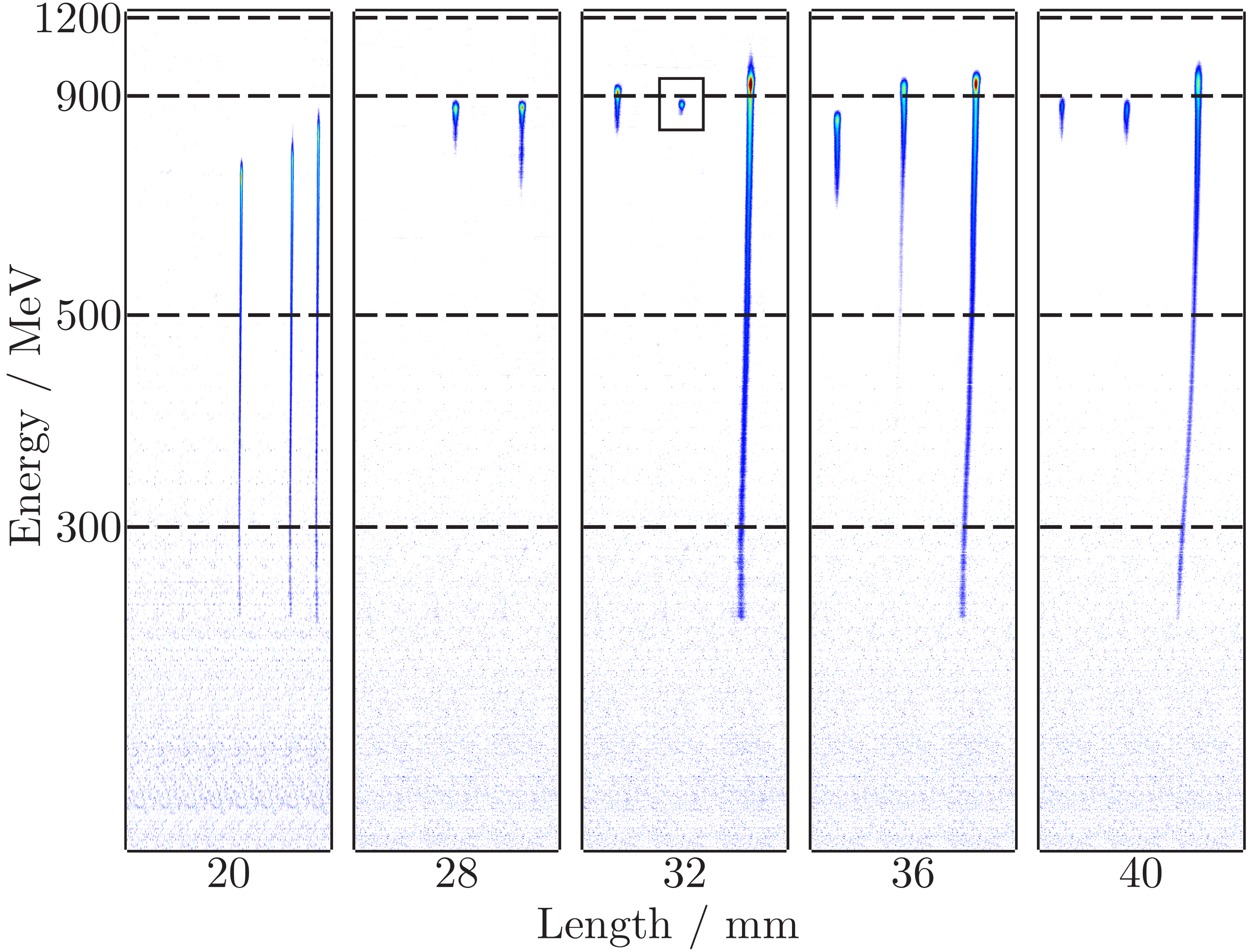


Energy on target
10.0 ± 0.3 J
$L_{cell} = 20$ mm

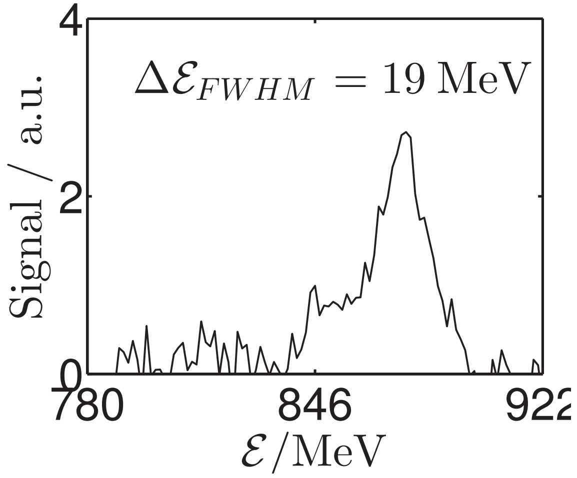
IC at CLF's GEMINI; 2015

credit: Z. Najmudin

Accelerating and guiding



Energy on target
9.5 ± 0.2 J
Backing pressure
55 mbar



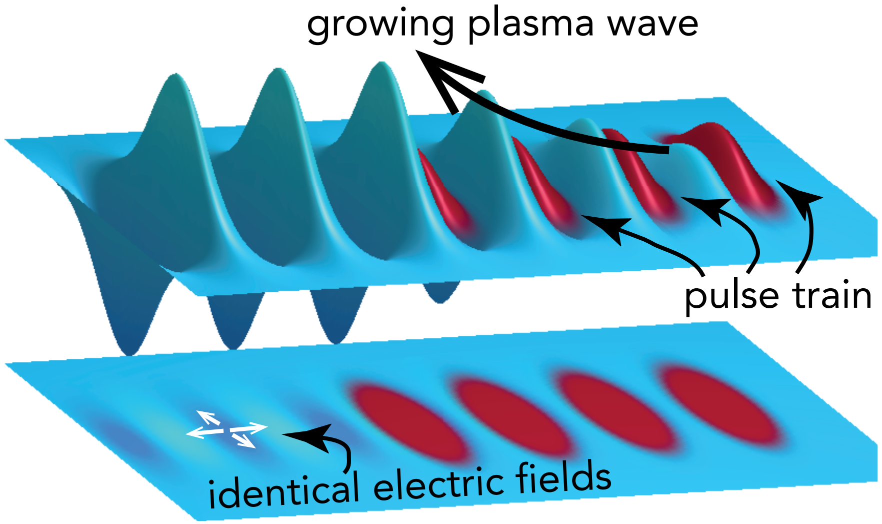
IC at CLF's GEMINI; 2015

credit: Z. Najmudin

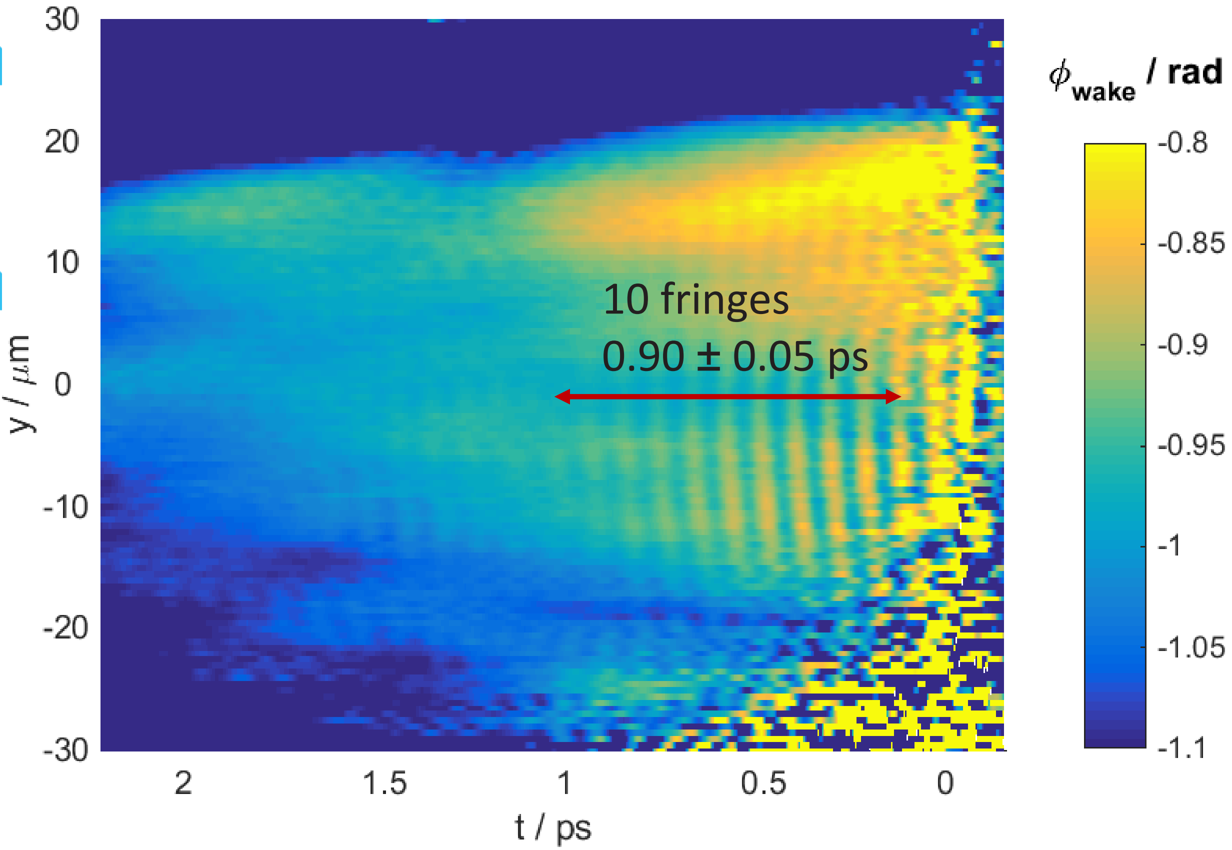
S.M. Hooker *et al. J. Phys. B* **47** 234003 (2013)

ASTRA TA2 at CLF

Split a single pulse into a train of pulses and use it in a proof-of-principle demonstration of MP-LWFA concept.
Method: Frequency Domain Holography



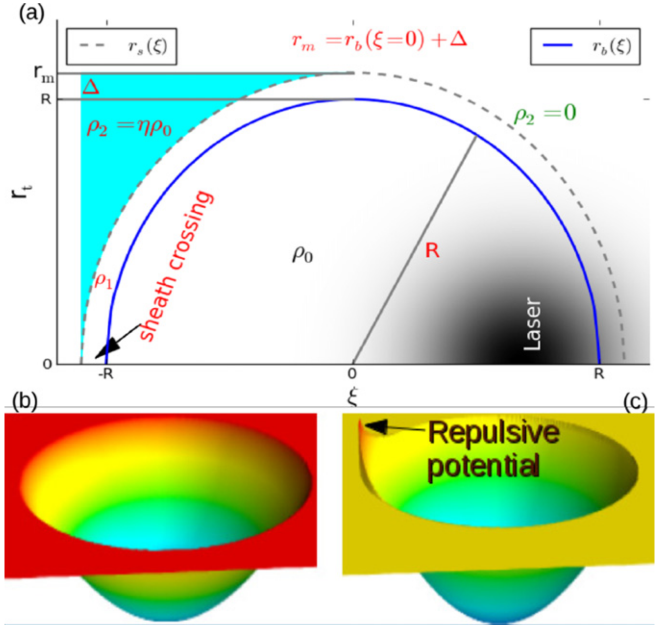
Multi-pulse LWFA
Only 4 laser pulses shown. In reality would use 10 - 100!



An example of interference fringes due to a plasma wake.
A paper in preparation.

Oxford at CLF's ASTRA; 2015

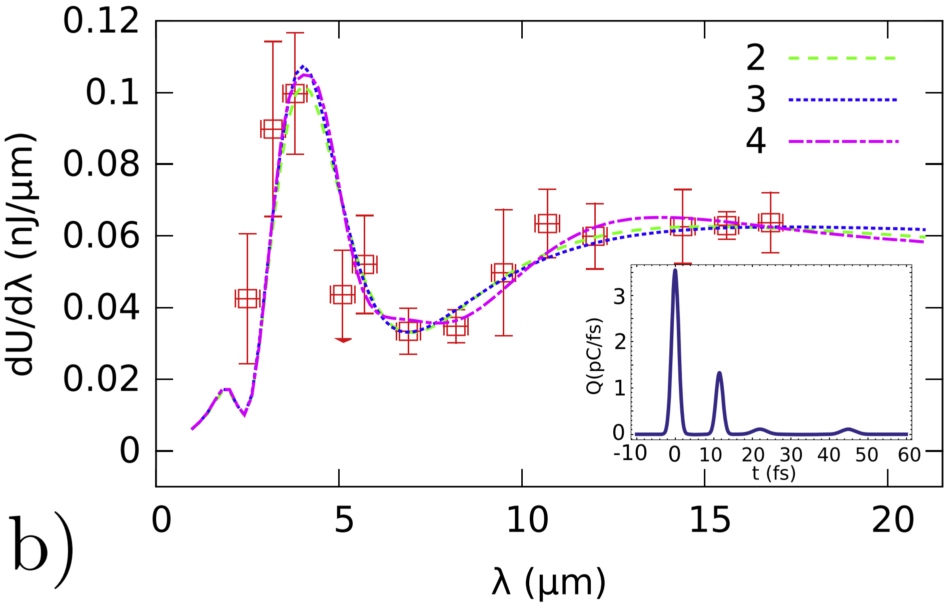
electron injection



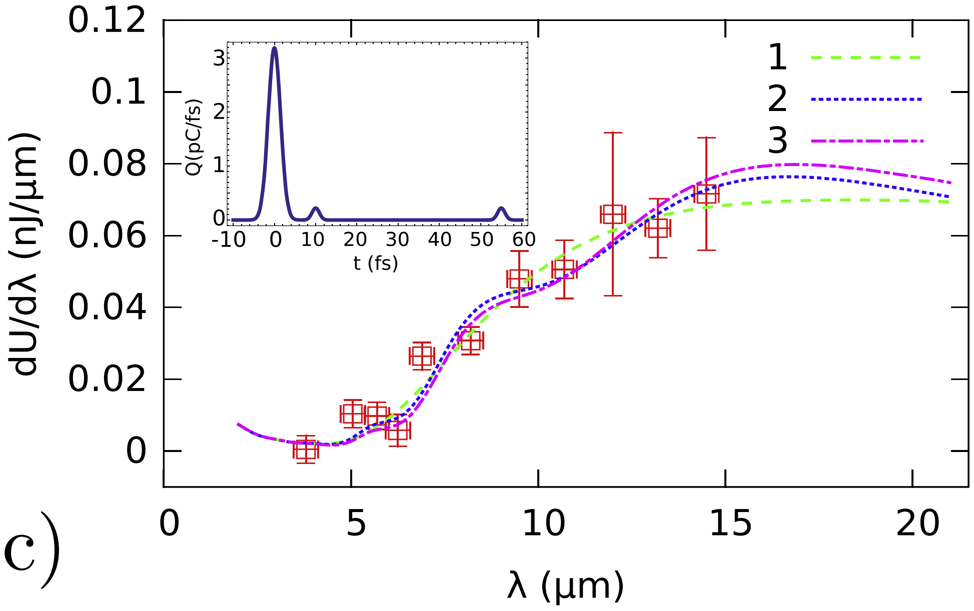
Near-threshold electron injection at the back of a plasma buble.

Measurements at ALPHA-X

M.R. Islam et al. New J. Phys. 17 (2015) 093033
Strathclyde and St. Andrews.



b)



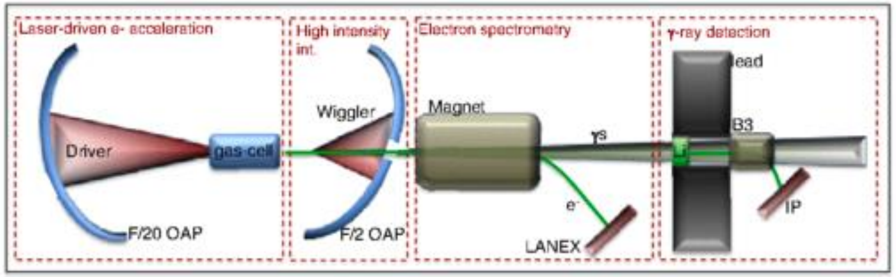
c)

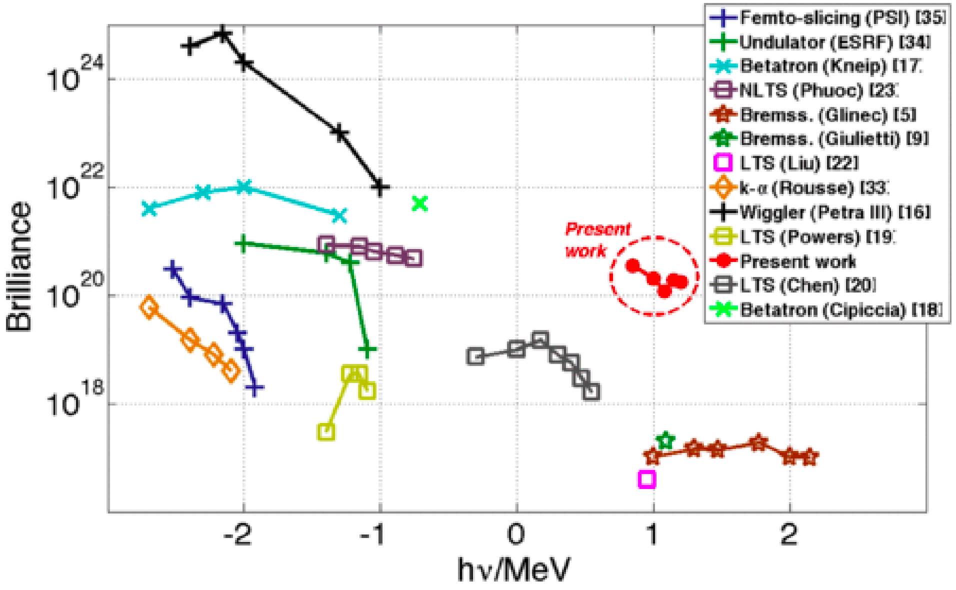
Brightest ever gamma ray source!

QUB-led team produced a gamma-ray beam in the multi-MeV range with highest peak brilliance ever produced!

They used nonlinear–Thompson scattering: scattering the north beam off an electron beam produced by the south beam

Gemini is uniquely placed to do such experiments with its dual-beam capability





Phys. Rev. Lett. **113**, 224801 (2014)

MPQ

Helmholtz Association
Helmholtz Institute Jena

Imperial College London

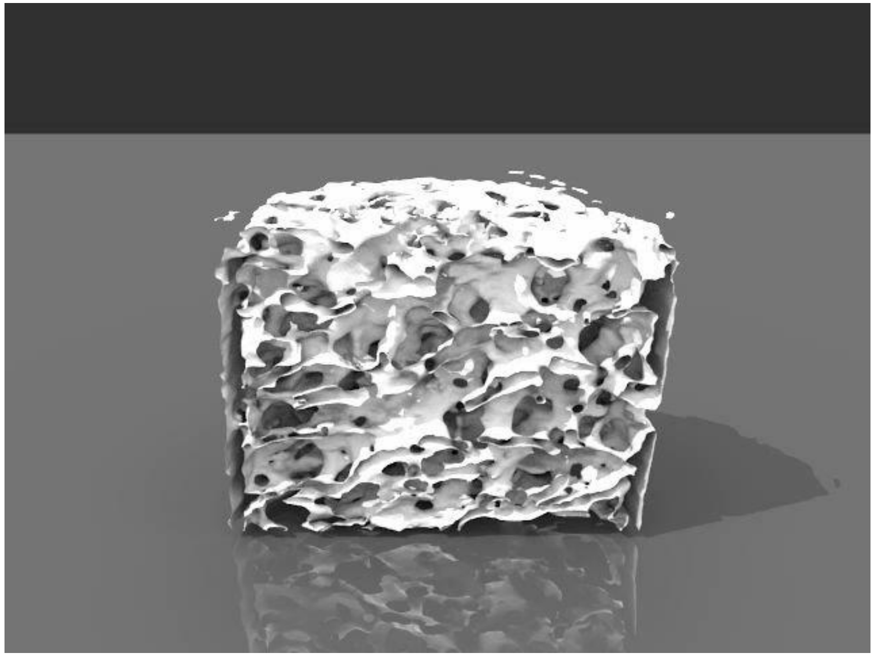
Queen's University Belfast

credit: R. Pattathil and G. Sarri

X-ray tomographic imaging using Gemini

Betatron x-rays generated by CLF’s GEMINI laser was used for tomographic imaging of trabecular bone tissues

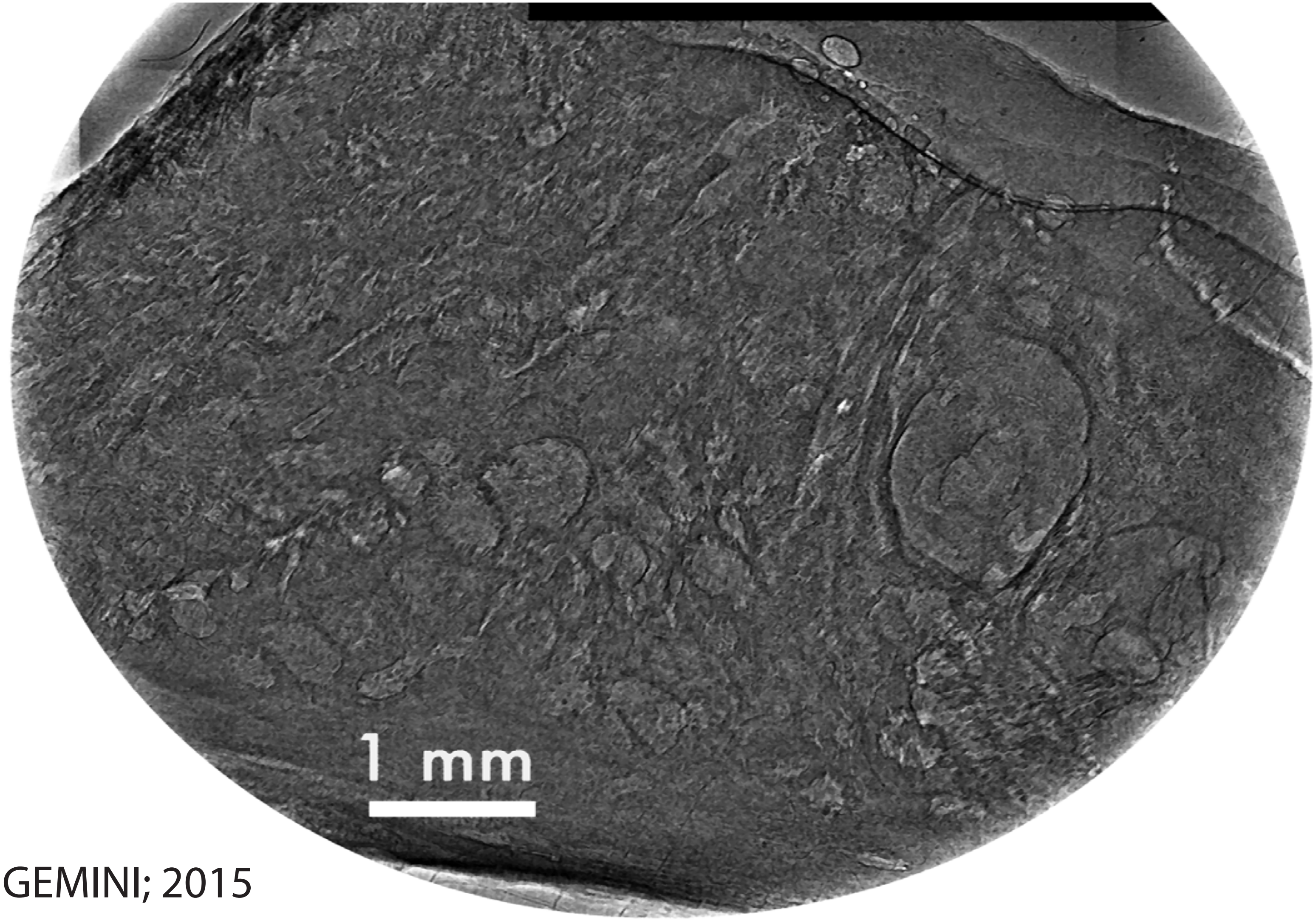
The semi-coherent x-rays produced by the laser accelerated electrons enable phase-contrast imaging, bringing the dream of compact, affordable high resolution x-ray imaging for medical and biological applications a step



Cole, Sci. Reports (2015)
https://www.llnl.gov/str/Sep06/Kinney.html
http://www.skyscan.be

credit: R. Pattathil and Z. Najmudin

Prostate Imaging with Gemini



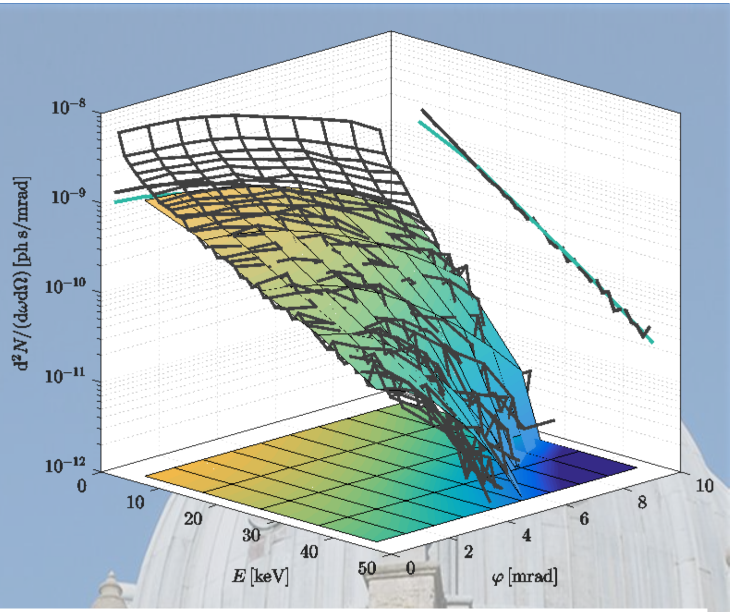
IC at CLF's GEMINI; 2015

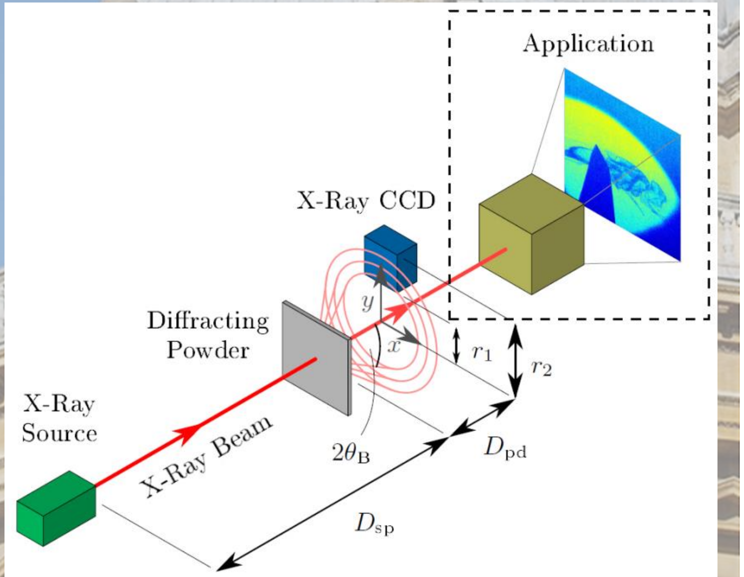
Lopes N. et al. X-ray phase contrast imaging of biological specimens with femtosecond pulses of betatron radiation from a compact laser plasma wakefield accelerator. In Preparation (2016).

credit: Z. Najmudin

X-ray Characterisation by Energy-Resolved Powder (XCERP) Diffraction

- Single-shot measurement of bright X-ray beams, e.g., betatron radiation from LWFAs
- Non-destructive technique to allow *simultaneous* measurement and application
- Measures angularly-resolved spectrum without requiring assumptions of spectral shape
- Powder diffraction from a *known* material used to infer details about the *unknown* X-ray beam
- Uses single photon method to resolve energy of photons incident on X-ray CCD





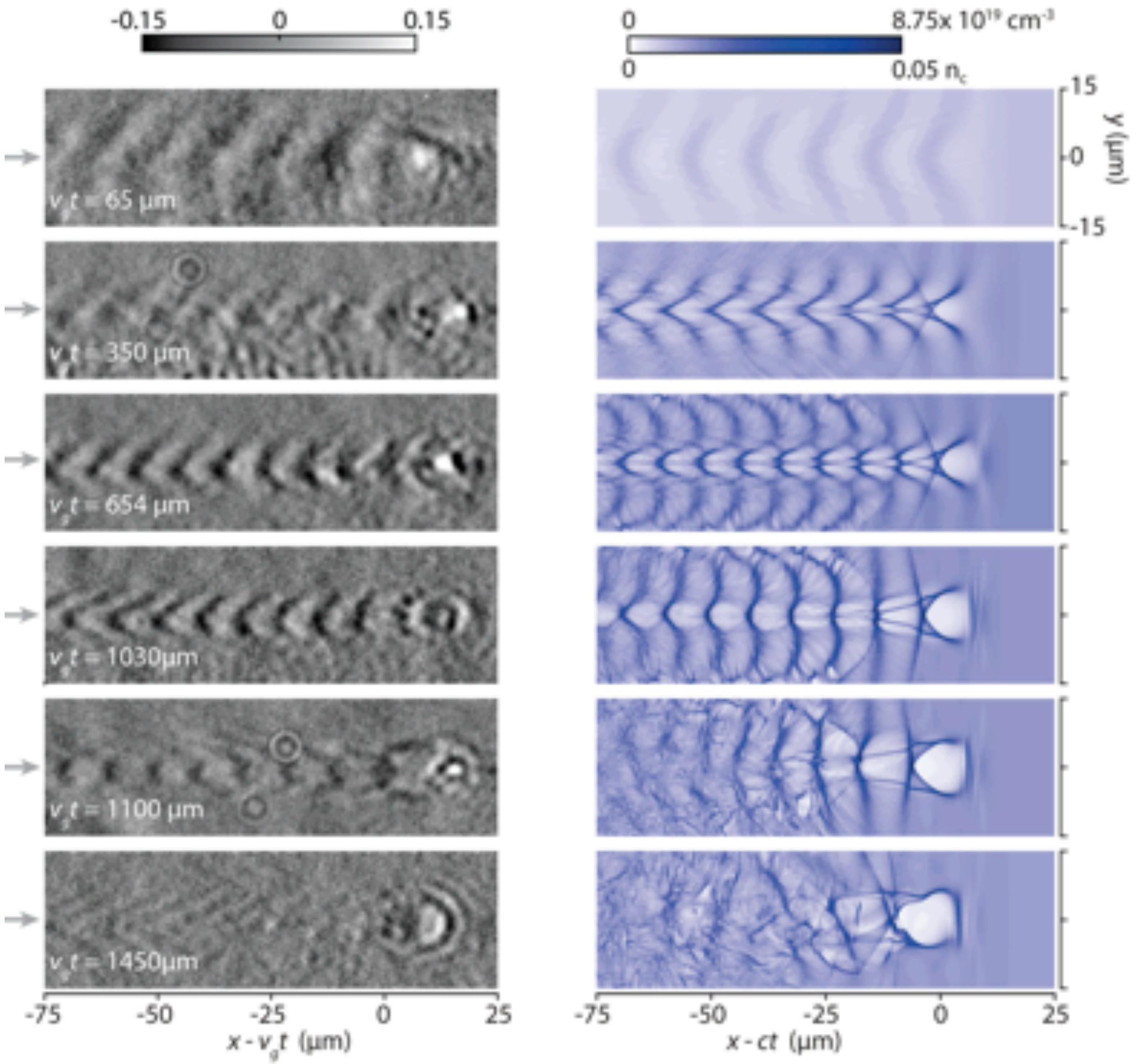
credit: G. Cheung; submitted for publication 2016

Diagnostics

A. Sävert, *et al. Phys. Rev. Lett.* **115**, 055002 (2015)

- Transverse shadowgraphy with ultrfast probe pulse
- Direct observation of wakefield
- Excellent agreement with simulations

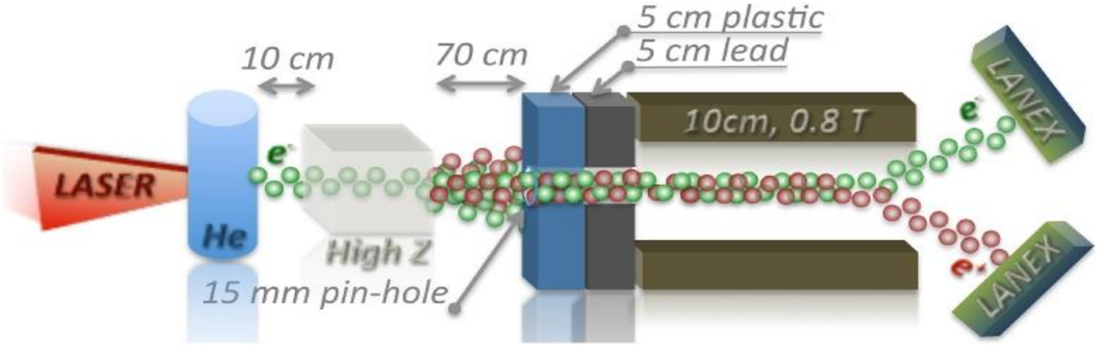
IC and IOQ Jena



credit: Z. Najmudin

Using Gemini to make copious electron-positron plasma

QUB-led experiment in Gemini creates copious amounts of electron-positron plasma.



Electron-positron plasmas are emitted by some of the most energetic or powerful objects in the Universe, such as black holes, pulsars and quasars. These plasmas are associated with violent emission of gamma-rays in the form of short-lived bursts, which are among the most luminous events ever observed in the Universe.

This experiment re-created some of these conditions in the laboratory

Nature Comm. 6, 6747 (2015)

Queen's University Belfast

HELMHOLTZ | ASSOCIATION

Helmholtz Institute Jena

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

CENTER FOR ULTRAFAST OPTICAL SCIENCE

Imperial College London

INFN Istituto Nazionale di Fisica Nucleare

INSTITUTO SUPERIOR TÉCNICO

Science & Technology Facilities Council

credit: R. Pattathil and G. Sarri

Theory

Strathclyde

- Currently 12 senior members (including Prof. Z.M. Sheng)
- Development of codes such as ICL, Betatron and CPL, PUFFIN; use of PIC codes such as *OSIRIS,VORPAL, EPOCH*, *WAKE*; fluid codes such as *MULTI, HELIOS*, etc.
- Relativistic laser-plasma based radiation sources from THz to gamma-rays, including transition radiation, mode conversion, Thomson/Compton scattering, betatron radiation, Raman amplification.

St. Andrews and CLF

Stimulated Raman and Brillouin scattering, in particular Raman and Briillouin amplification.
Photon accelerationas a wakefield diagnostics.
Relaxation of the wakefield in plasma channels for high rep rate operation.
Beam loading.

Lancaster

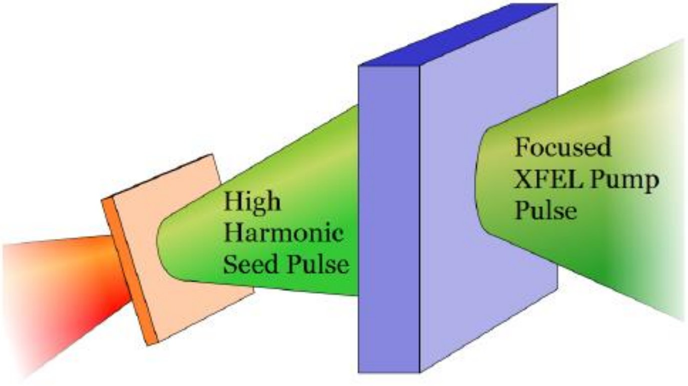
Investigated the implications of Stern-Gerlach-type forces in laser wakefield accelerators.
Developed a new kinetic theory of radiation reaction.
Developed a fundamentally new formulation of radiation reaction of electrons in ultraintense laser fields based on higher order Maxwell electrodynamics.
Developed a new simulation tool for Laser-Plasma interactions using spatially compact finite energy laser pulses.

Warwick

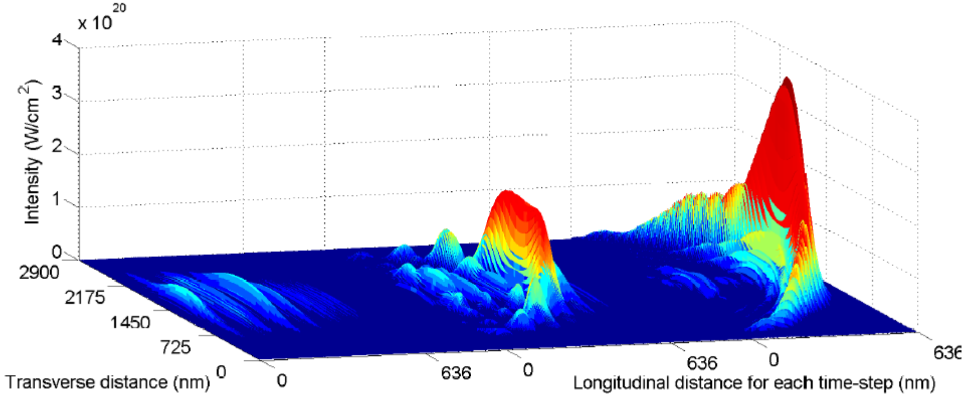
Development and maintenance of EPOCH PIC code.

credit: B. Hidding, J. Gratus, A. Cairns and B. Bingham

Energetic coherent attosecond pulse generation



Concept



Amplification of seed pulse

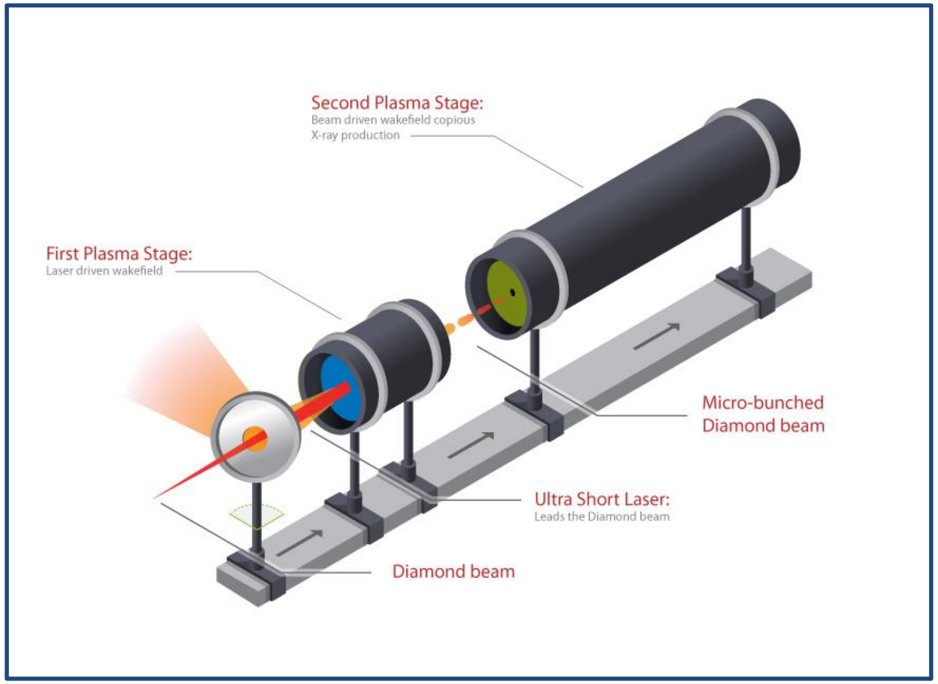
Raman amplification of X-ray lasers – simulations match analytic model to show that coherent mJ, 0.4 fs, 1-10 nm laser pulses can be generated using high power lasers coupled to XFEL's

J. Sadler *et al*., Scientific Reports **5**, 16755 (2015) Oxford, CLF and Strathclyde

credit: P. Norreys

e-driven

A plasma wiggler for the Diamond Light Source

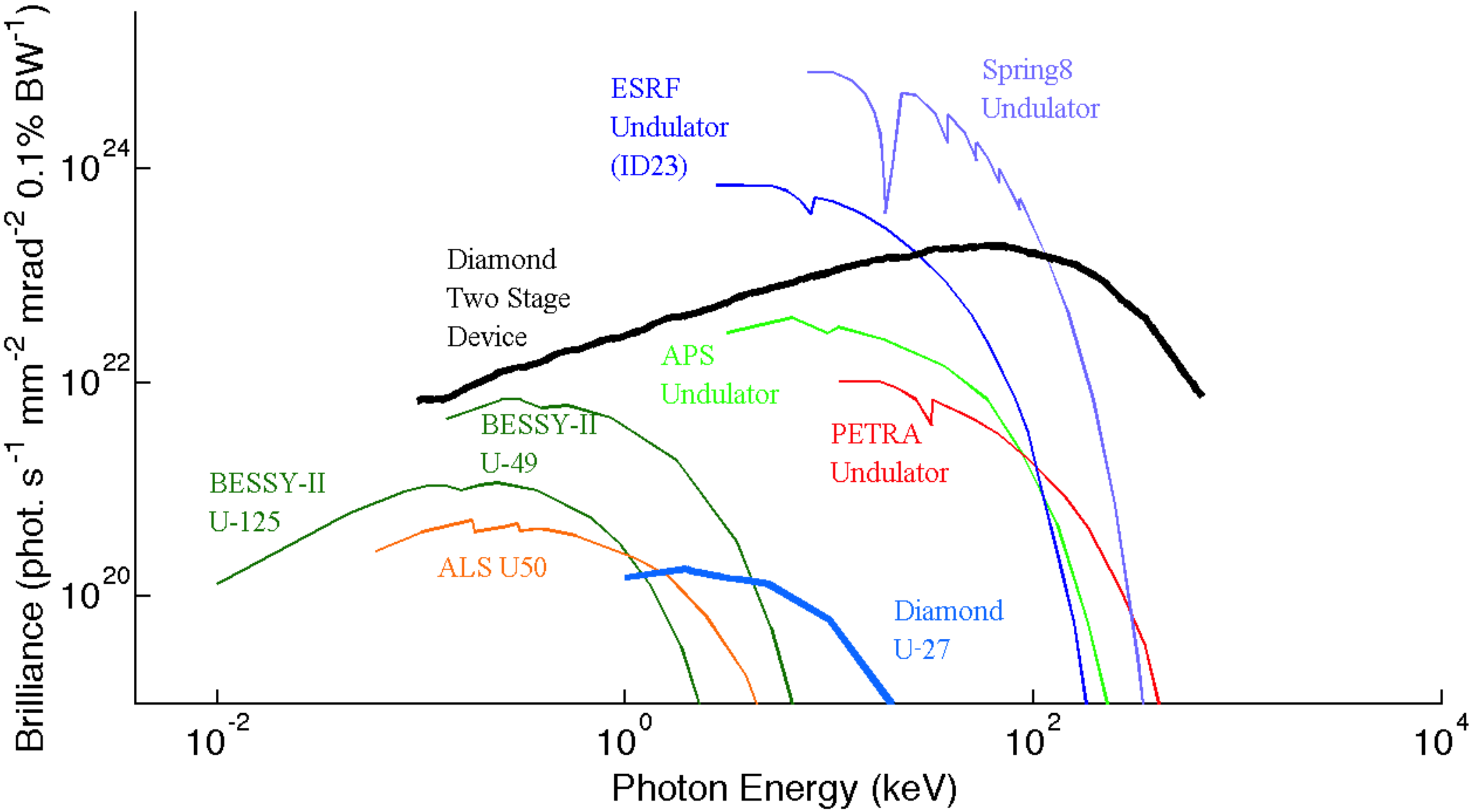


Dr Jimmy Holloway –submitted to Scientific Reports March 2016

Collaboration between University College London, the John Adams Institute, University of Michigan, the Diamond Light Source and the Central Laser Facility

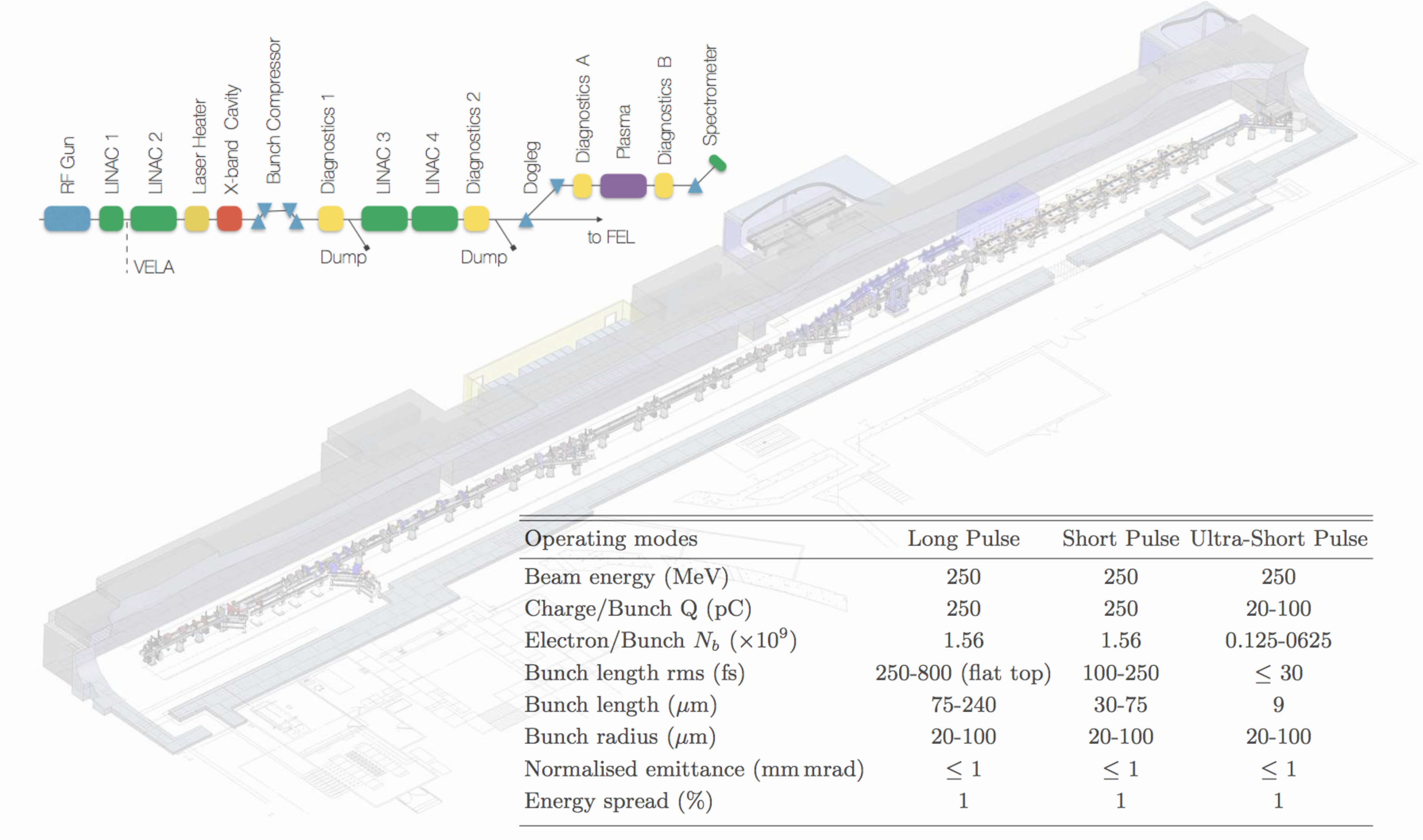
credit: P. Norreys

A plasma wiggler for the Diamond Light Source



credit: P. Norreys

Plasma Accelerator Research Station/PARS



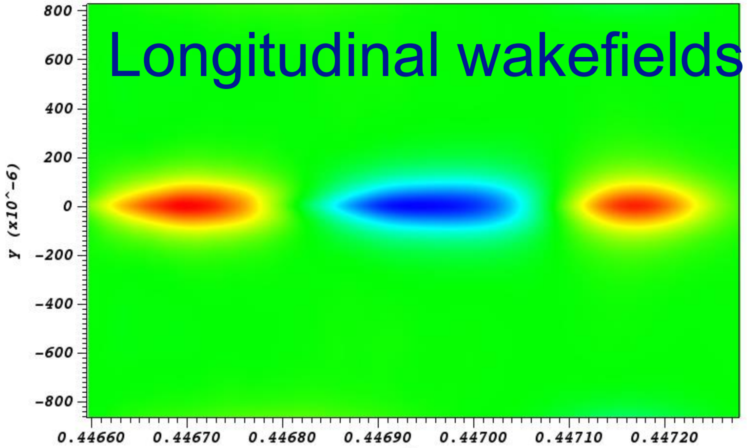
Operating modes	Long Pulse	Short Pulse	Ultra-Short Pulse
Beam energy (MeV)	250	250	250
Charge/Bunch Q (pC)	250	250	20-100
Electron/Bunch N_b ($\times 10^9$)	1.56	1.56	0.125-0625
Bunch length rms (fs)	250-800 (flat top)	100-250	≤ 30
Bunch length (μm)	75-240	30-75	9
Bunch radius (μm)	20-100	20-100	20-100
Normalised emittance (mm mrad)	≤ 1	≤ 1	≤ 1
Energy spread (%)	1	1	1

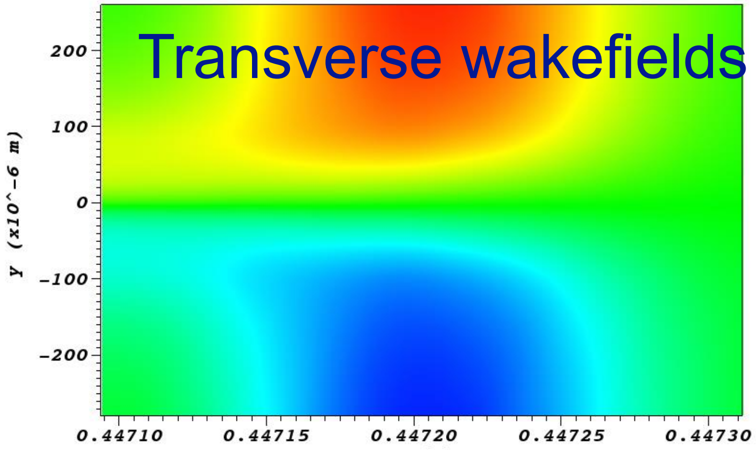
in collaboration with Deepa Angal-Kalinin and other ASTeC and CI colleagues

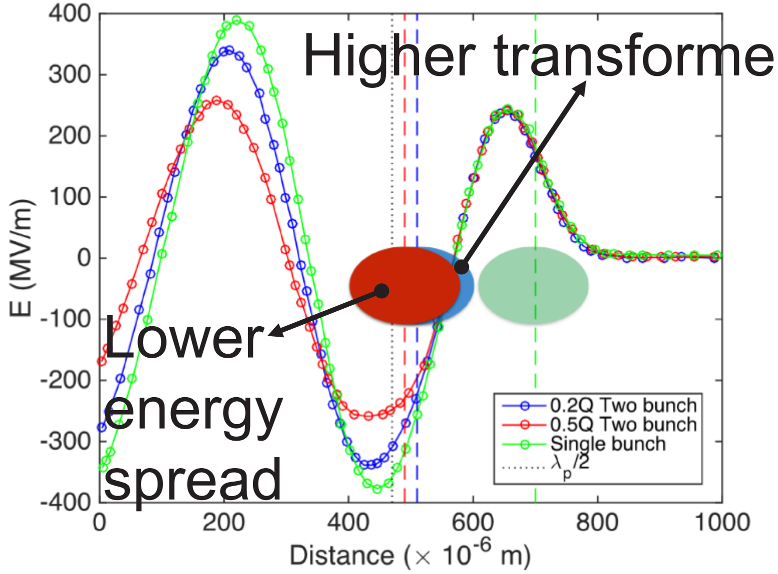
credit: Q. Xia

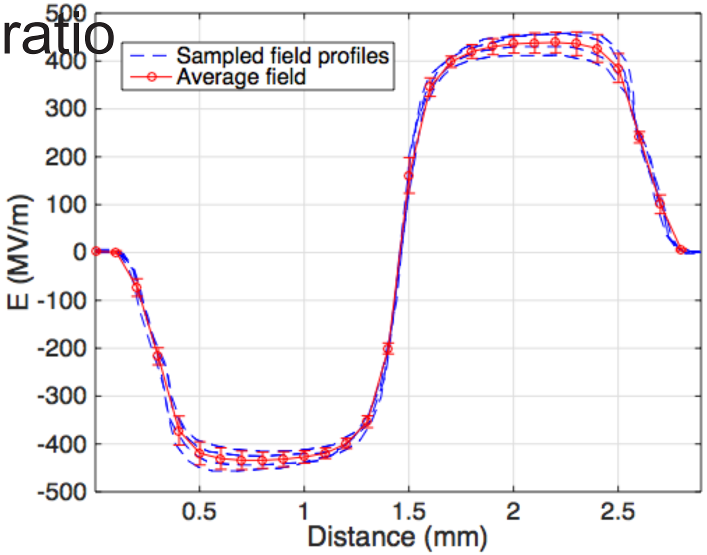
Two Bunches

PARS Project









Manchester
ASTeC
Strathclyde
Liverpool
Lancaster

with some help from
IC and Oxford

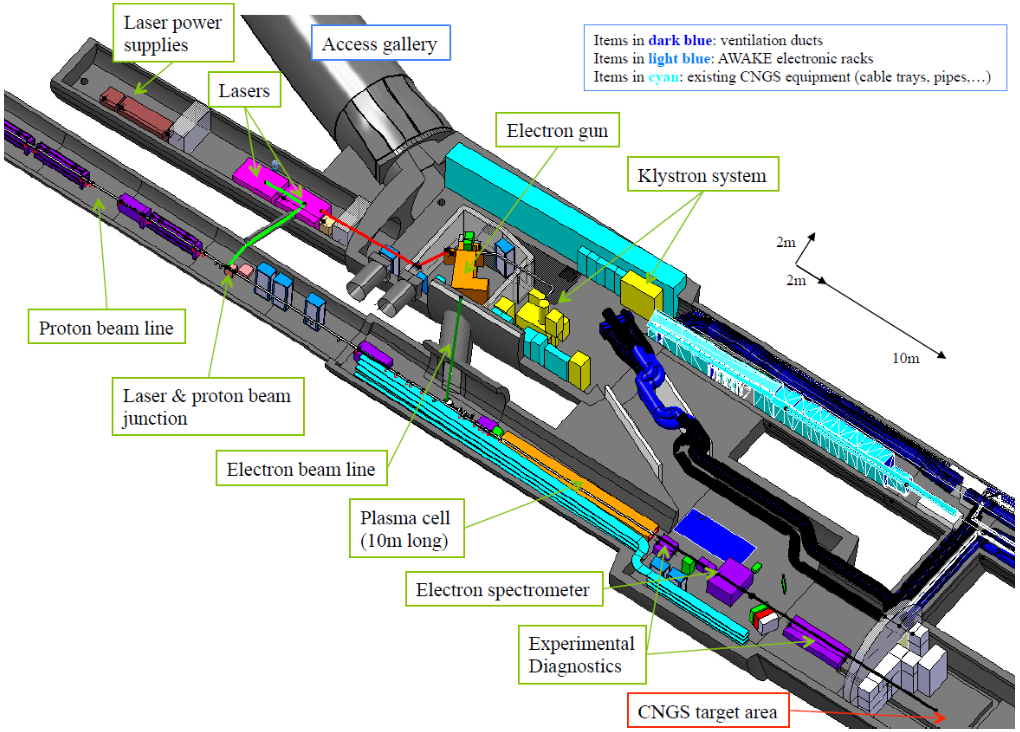
O. Mete, et al.,Physics of Plasmas 22, 103117 (2015)

credit: Q. Xia

AWAKE proof-of-principle experiment CERN

Towards a TeV e^-e^+ collider using a proton-driven wakefield accelerator

Novel photon acceleration diagnostic to measure the wakefield amplitude growth along the plasma column concept developed in Oxford Physics, the John Adams Institute and the Central Laser Facility.



Oxford
CLF
Strathclyde
UCL

M. Kasim *et al.,* Phys. Rev. ST Accel. Beams **18**, 030402 (2015)
M. Kasim et al., Phys. Rev. ST Accel. Beams **18**, 081302 (2015)

credit: P. Norreys

Good news!

Significant investments at Lancaster University:

The group becomes bigger

two new Professors

and 5 new PDRAs

Good news!

Alec Thomas: Joining Lancaster University in May 2016

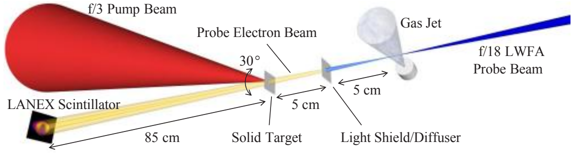
2014 – 2016, Associate Professor, University of Michigan
2008 – 2014, Assistant Professor, University of Michigan
2007, PhD Plasma Physics, Imperial College London

Research: Experimental/Theoretical laser-plasma interactions / Laser Wakefield Acceleration

Recent research:

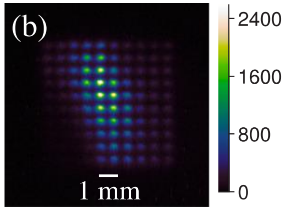
- Bright and spatially coherent laser-plasma sources of X-rays
    - The X-rays generated from betatron oscillations in laser wakefield accelerators [1] emanated from a small source [2,3] and have femtosecond duration [4] and scale up to high power [5].
- Nonlinear inverse Compton scattering and positron sources using LWFAs
    - LWFA accelerated electrons were used for a compact all-optical inverse Compton scattering source [6] and positron sources on a tabletop [7,8].
- High repetition rate laser wakefield acceleration with a 10 mJ laser:
    - Generating electrons by plasma wakefield acceleration on a downramp at 500 Hz [9] to explore high-repetition rate operation of LWFA such as the use of feedback systems and emittance control [10].
- Radiation Reaction in Intense Laser Interactions with Relativistic Electrons:
    - Radiation reaction is an unsolved theoretical problem. We have modeled this for proposed nonlinear inverse Compton scattering [11] and laser-solid interaction experiments [12].

fs pump-probe measurements

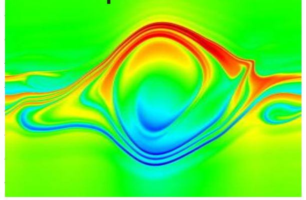


X-ray phase contrast imaging

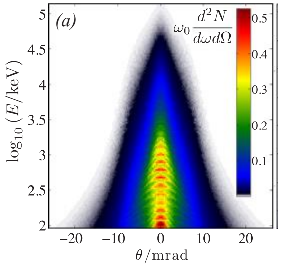
LWFA emittance control



Relativistic plasma kinetics



Nonlinear Compton Scattering



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Good news!

Louise Willingale: Joining Lancaster University in May 2016

2014 – 2016, Assistant Professor, University of Michigan

2008 – 2011, Postdoc, 2011 – 2014, Assistant Research Scientist, University of Michigan

2007, PhD Plasma Physics, Imperial College London

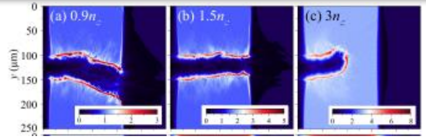
Research: Experimental high-intensity laser plasma interactions / ion acceleration

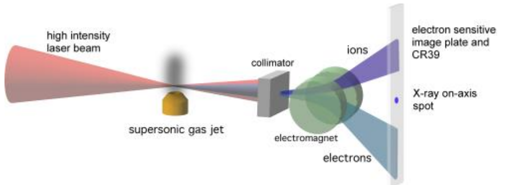
The Cockcroft Institute of Accelerator Science and Technology

Previous research:

- Laser-driven ion acceleration from underdense and near-critical density plasmas
- Laser-driven ion acceleration via Target Normal Sheath Acceleration (TNSA)
- Proton radiography of laser plasma interactions
- Relativistic intensity channel formation
- Direct Laser Acceleration (DLA) of electrons
- Relativistically Induced Transparency effects
- Laser-driven magnetic reconnection

L Willingale, et al, Physical Review Letters, **102**, 125002 (2009)





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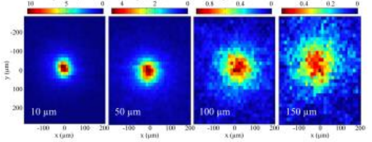

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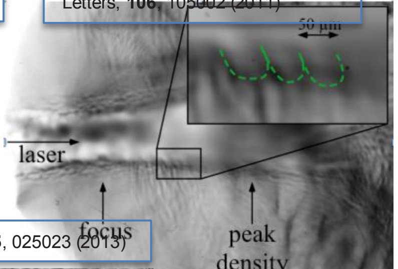

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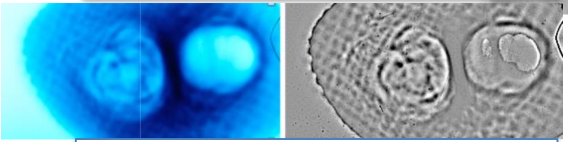


L Willingale, et al, Physics of Plasmas, 17, 043104 (2010)

Good news!

Future work at Cockcroft/Lancaster experimental plasma based accelerators

The Cockcroft Institute
of Accelerator Science and Technology

- Photon sources using laser driven wakefield accelerators
- Strong field physics relevant to plasma based accelerator schemes
- Beam driven plasma wakefield acceleration
- High repetition-rate laser wakefield acceleration and detailed control of plasma waves
- Laser-Driven Collisionless Shock Ion Acceleration
- Direct Laser Acceleration of Electrons
- Relativistically Induced Transparency (RIT) in Plasmas

credit: A. Thomas

Good news!

SCAPA

D. Jaroszynski (director), P. McKenna, Z.-M. Sheng, B. Hidding, M. Wiggins, G. Welsh, R. Gray, K. Ledingham. **et al.**

Scottish Centre for the Application of Plasma-based Accelerators

- Collaborative research opportunity for the whole faculty, Scotland and the UK!
- £8M investment + additional infrastructure funds (SFC, SUPA, UoS..)
- Accelerator and Light Source R&D
- Strong engagement in European and other large projects
- In-depth programme of **applications, knowledge exchange & commercialization**

- 3 high-power laser systems, initially up to 350 TW (40 TW ALPHA-X laser now, 350 TW in 2016)
- 3 shielded radiation caves, fully vibration-isolated, w/ 2000 tons of concrete shielding
- up to 7 accelerator application beam lines for programmatic R&D
- ~1200 m^2 on two levels
- High-energy particle beams: electrons, protons, ions, positrons, neutrons
- High-energy photon beams: fs duration, (coherent) VUV, X-ray & gamma-rays

credit: B. Hidding

Good news!

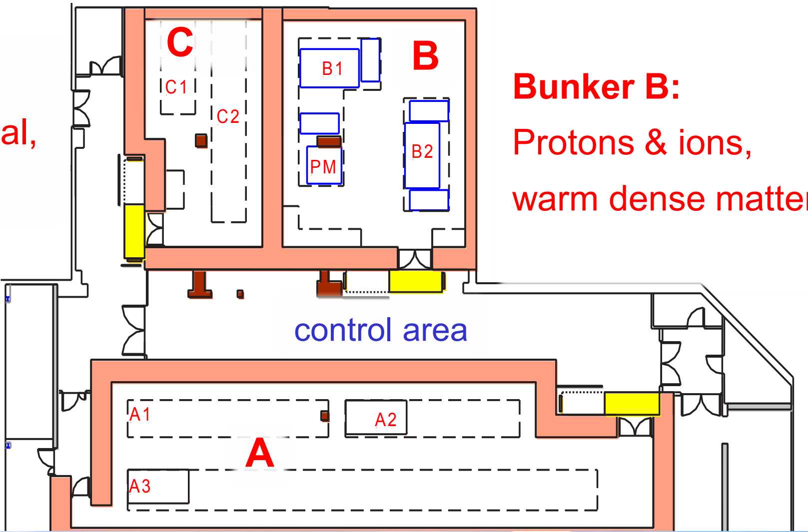
SCAPA

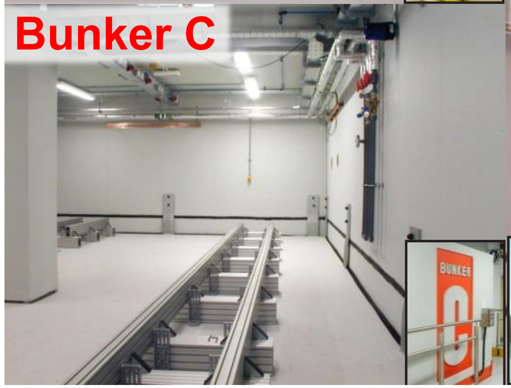
SUPA

Level 1: radiation caves, level 2: laser clean rooms

Bunker C:
Health, medical,
life sciences

Bunker B:
Protons & ions,
warm dense matter





credit: B. Hidding

EuPRAXIA – Addressing the Quality Issue

Horizon2020

- Our question for the next 4 years:

  <u>Assuming no resource limits – What would be the best 1 – 5 GeV e- plasma accelerator we can build? And what could we use it for (pilot users)?</u>

NOVEL FUNDAMENTAL RESEARCH

COMPACT EUROPEAN PLASMA ACCELERATOR WITH SUPERIOR BEAM QUALITY

"RF unit test" for plasma accelerators

European Network EuroNNAc for Novel Accelerators

EuPRAXIA

The EuPRAXIA Steering & WP Leader Team

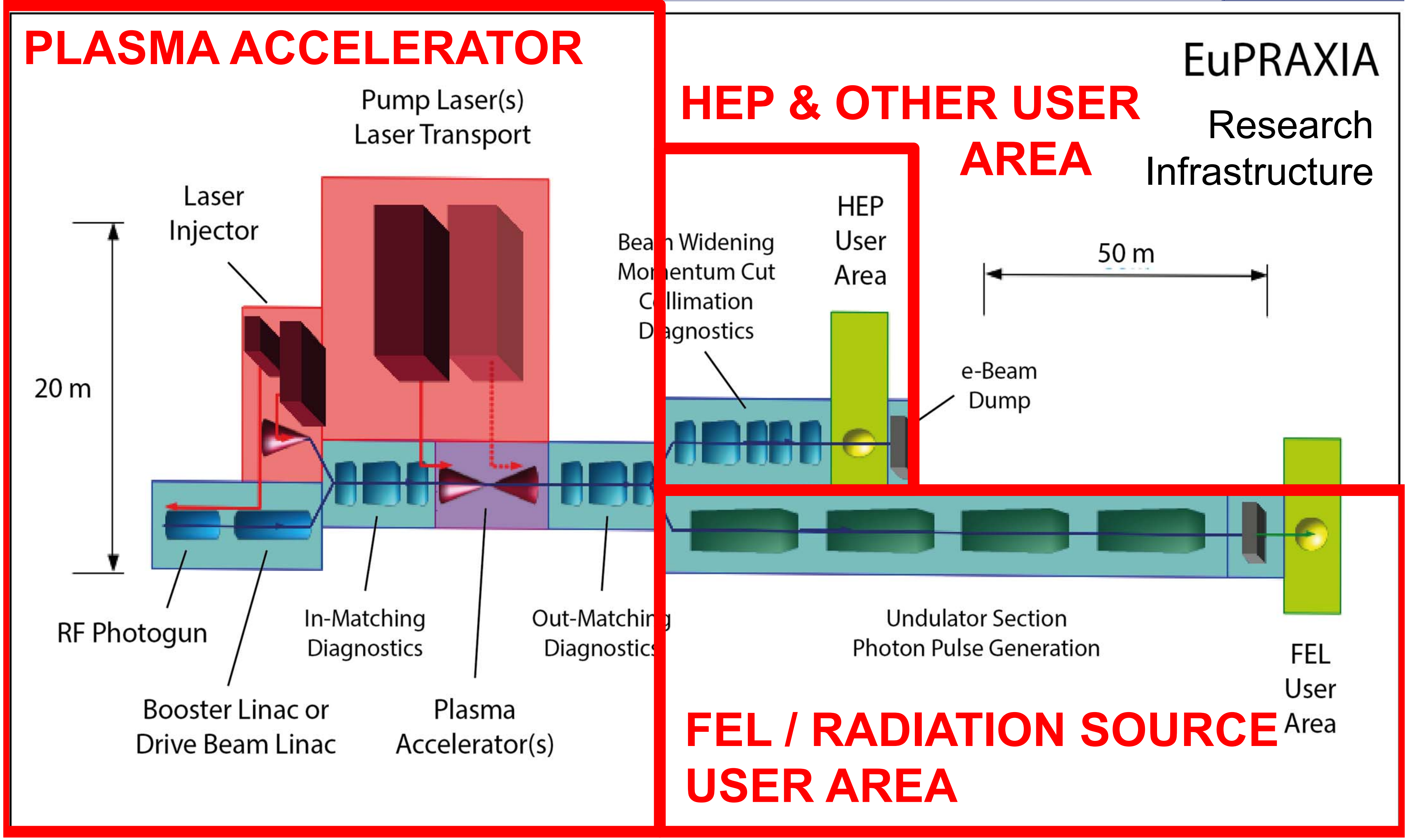
Horizon2020

DESY
INFN
Consiglio Nazionale delle Ricerche
cnrs
University of Strathclyde Glasgow
cea
SAPIENZA Università di Roma
SOLEIL SYNCHROTRON
University of Liverpool
IST-ID Associação do Instituto Superior Técnico para a Investigação e Desenvolvimento
Imperial College London
University of Oxford
ENEA Italian National Agency for New Technologies, Energy and Sustainable Economic Development
Science & Technology Facilities Council
UHH Universität Hamburg
MANCHESTER 1824 The University of Manchester

plus 18 associated partner institutes


Kick-off meeting at DESY on Nov 26th – 27th

Schematic Layout EuPRAXIA Research Infrastructure

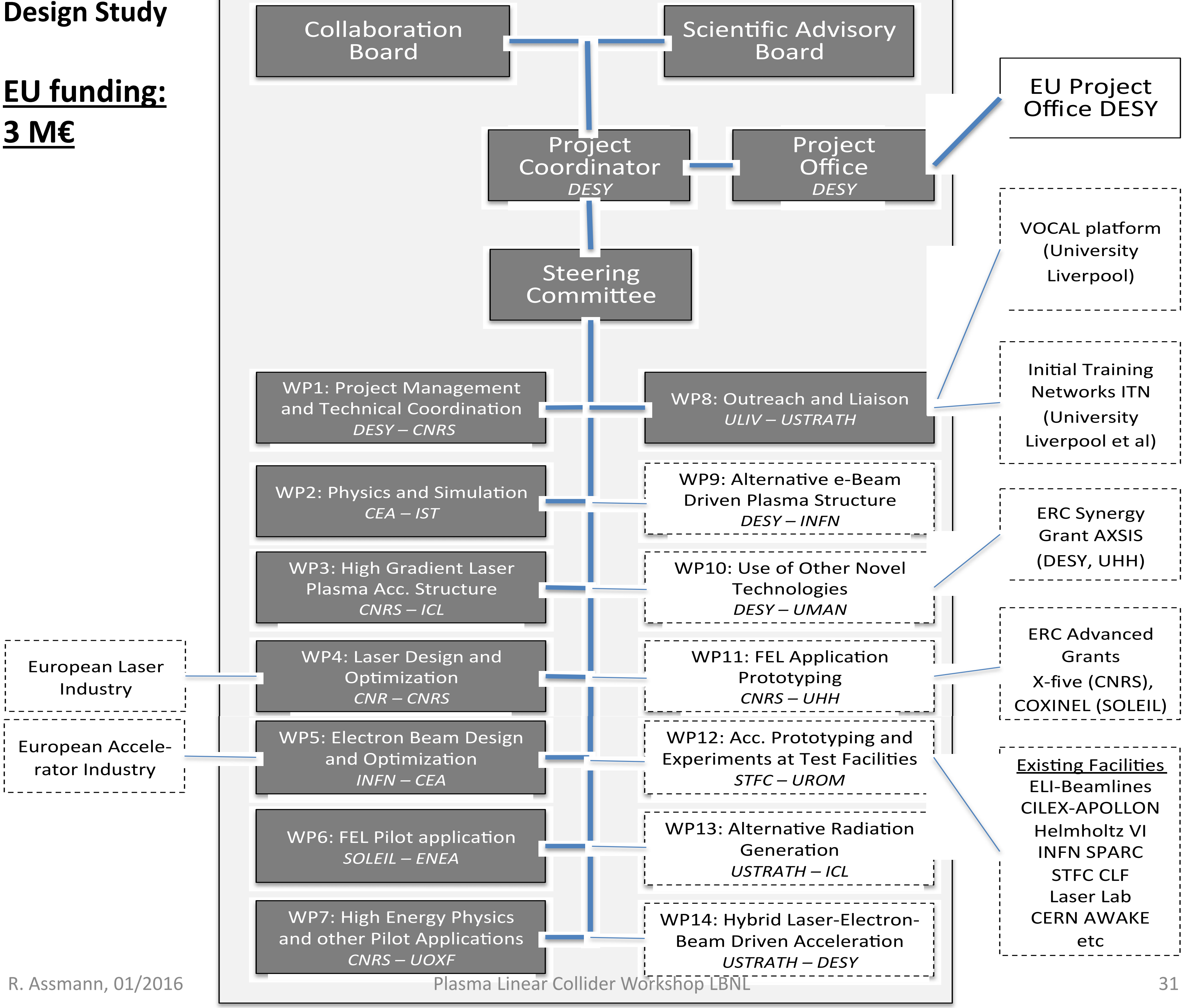


Beam Parameter	Unit	Value
Particle type	-	Electrons
Energy	GeV	1 – 5
Charge per bunch	pC	1 – 50
Repetition rate	Hz	10
Bunch duration	fs	0.01 - 10
Peak current	kA	1 – 100
Energy spread	%	0.1 – 5
Norm. emittance	mm	0.01 – 1
FEL wavelength	nm	1 - 15

Table 1.1: Electron beam parameters as presently foreseen. A commercially available laser driver (e.g. currently available 1 PW Ti: Sa laser) or a custom built electron beam could be adequate drivers for the plasma acceleration. The parameters give access (1) to an FEL in the EUV to X-ray regime (1 – 15 nm) and (2) to short electron pulses with high brightness for HEP detector tests, material tests and other applications.

Design Study

EU funding:
3 M€



Collaboration Board

Scientific Advisory Board

EU Project Office DESY

Project Coordinator
DESY

Project Office
DESY

Steering Committee

VOCAL platform (University Liverpool)

Initial Training Networks ITN (University Liverpool et al)

ERC Synergy Grant AXSIS (DESY, UHH)

ERC Advanced Grants
X-five (CNRS),
COXINEL (SOLEIL)

Existing Facilities
ELI-Beamlines
CILEX-APOLLON
Helmholtz VI
INFN SPARC
STFC CLF
Laser Lab
CERN AWAKE
etc

European Laser Industry

European Accelerator Industry

WP1: Project Management and Technical Coordination
DESY – CNRS

WP2: Physics and Simulation
CEA – IST

WP3: High Gradient Laser Plasma Acc. Structure
CNRS – ICL

WP4: Laser Design and Optimization
CNR – CNRS

WP5: Electron Beam Design and Optimization
INFN – CEA

WP6: FEL Pilot application
SOLEIL – ENEA

WP7: High Energy Physics and other Pilot Applications
CNRS – UOXF

WP8: Outreach and Liaison
ULIV – USTRATH

WP9: Alternative e-Beam Driven Plasma Structure
DESY – INFN

WP10: Use of Other Novel Technologies
DESY – UMAN

WP11: FEL Application Prototyping
CNRS – UHH

WP12: Acc. Prototyping and Experiments at Test Facilities
STFC – UROM

WP13: Alternative Radiation Generation
USTRATH – ICL

WP14: Hybrid Laser-Electron-Beam Driven Acceleration
USTRATH – DESY

European Network EuroNNAc for Novel Accelerators

EuPRAXIA

EuPRAXIA Contractual Deliverable with EU

Horizon2020

- Produce with EU funded manpower by end of 2019 an outstanding design report for **European 5 GeV plasma accelerator with superior beam quality & pilot applications**:
  - Include technical description with full performance estimates.
  - Include full cost estimate.
  - Include options for sites in Europe, both by partners and associated partners. Aim for open and friendly site competition. My view: If we get a next step project (1XX M€) anywhere → major success!
- International associated partners and industry are involved from the beginning → keep it open within rules.
- In 2020: EU and national funding agencies have required info for decision on future accelerator research infrastructures.

Summary

- ► UK belongs to the leaders of the field since day one.

- ► There is a reach spectrum of high quality research

- ► EuPRAXIA (significant UK participation) provides a framework for coherent research in Europe.

- ► Researchers in the UK have started a process leading to better coordination of their research across UK which in turn would make an impact of UK reserach on the field even bigger. It would also lead to UK policy regarding large projects in the UK and in Europe; such as for example EuPRAXIA European plasma accelerator which might be built somewhere.