Laser-Plasma Acceleration – Towards a Compact X-ray Light Source and FEL

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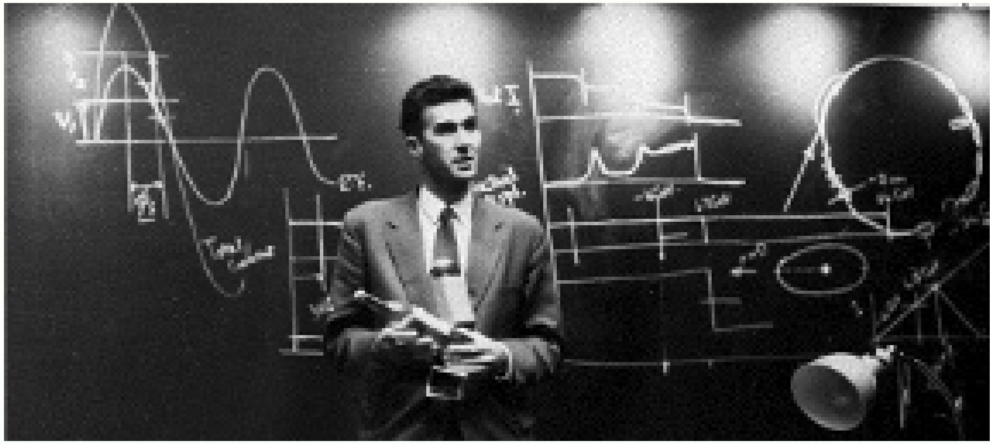
John Adams Institute for Accelerator Science

What is JAI

- **The John Adams Institute for Accelerator Science is a centre of excellence in the UK for advanced and novel accelerator technology, created in 2004 to foster accelerator R&D in the universities**

- **JAI is based on 3 universities: University of Oxford and RHUL initially, with Imperial College joining JAI in 2011**

- **JAI scale: ~25 academic professorial staff, ~15 research staff, ~10 affiliates, ~30 post-grad students, produce ~6PhD/year in Acc. science**



Sir John Adams (24 May 1920 - 3 March 1984) was the 'father' of the giant particle accelerators which have made CERN the leader in the field of high energy physics. John Adams worked at the UK Atomic Energy Research establishment on design & construction of a 180 MeV synchro-cyclotron. He then came to CERN in 1953 & was appointed director of the PS division in 1954. In 1961-66 Adams worked as director of the UK Culham Fusion Lab. In 1971 he returned to CERN and served until 1975 as Director-General of then called Laboratory II, responsible for the design & construction of the SPS. From 1976-80 he was executive DG of CERN and instrumental in approval of LEP. John Adams was a foreign member of Russian Academy of Science. On the photo above Adams announcing that CERN just passed the Dubna's Synchrophasotron world record of 10GeV.

http://www.adams-institute.ac.uk

Imperial College London | Royal Holloway University of London | UNIVERSITY OF OXFORD

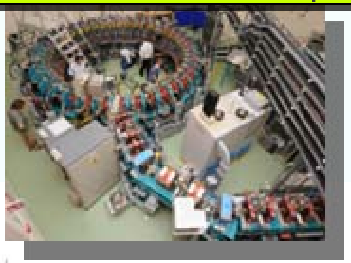
JAI within the UK SciTech ecosystem


Diamond Light Source


Central Laser Facility


Daresbury Science & Innovation Campus


ISIS neutron source




Accelerator Science &Technology Centre


Rutherford Lab & Harwell-Oxford Innovation campus

JAI is part of the world's most highly-regarded university fostered innovation ecosystem

University of Oxford

ISIS Innovation

Imperial College London

Imperial Innovations

JAI John Adams Institute for Accelerator Science

Royal Holloway University of London

Harwell Oxford Science | Technology | Business

Daresbury Science & Innovation Campus

ISIS

RAL CLF Diamond

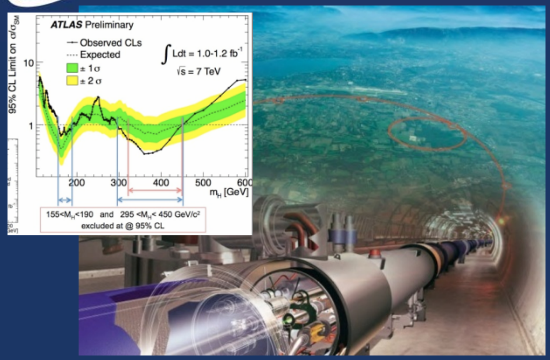
Research & Enterprise

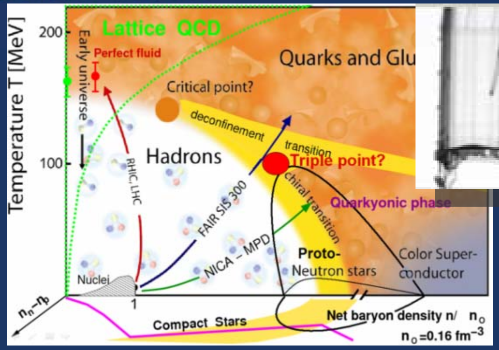
DL ASTeC

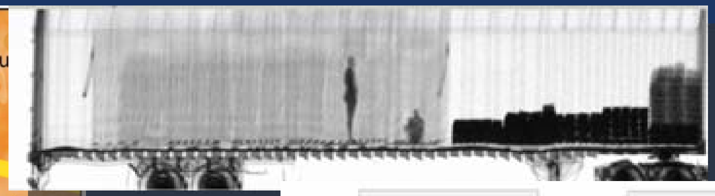
John Adams Institute for Accelerator Science

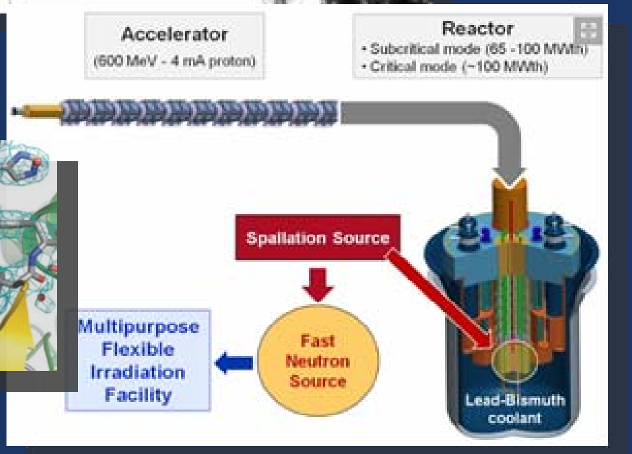
Imperial College London | Royal Holloway University of London | University of Oxford

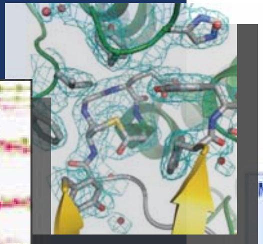
Accelerators for science and society

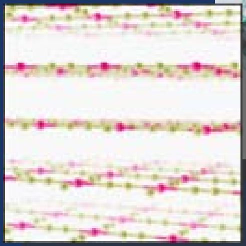


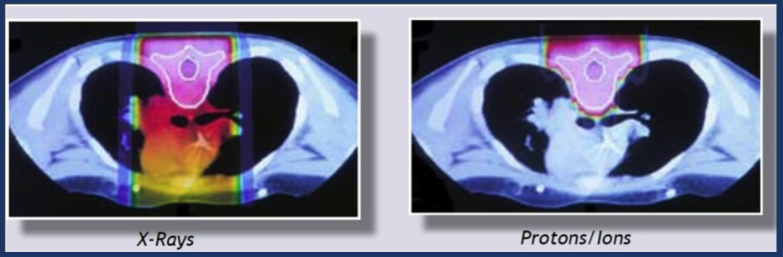












Accelerators: high energy physics, nuclear physics, healthcare, security, energy, life science, novel materials, industry, …

Tens of millions of patients receive accelerator-based diagnoses and treatment each year in hospitals and clinics around the world

All products that are processed, treated, or inspected by particle beams have a collective annual value of more than $500B

The fraction of the Nobel prizes in Physics directly connected to accelerators is about 30%

JAI research directions

Outreach & Industrial Connection

John Adams Institute for Accelerator Science

Enabling accelerator techniques for scientific, medical and energy applications

Next generation compact light sources and laser-plasma acceleration FEL

Advanced accelerator instrumentation, diagnostics and devices

IMPACT

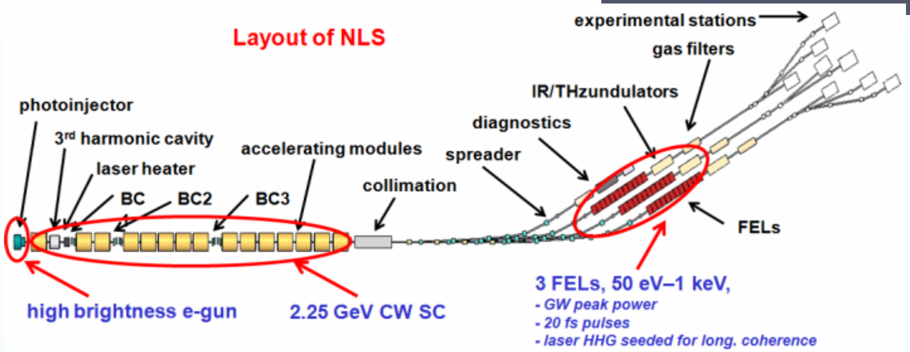
- Discovery Science
- Industry
- Energy challenges
- Societal benefit

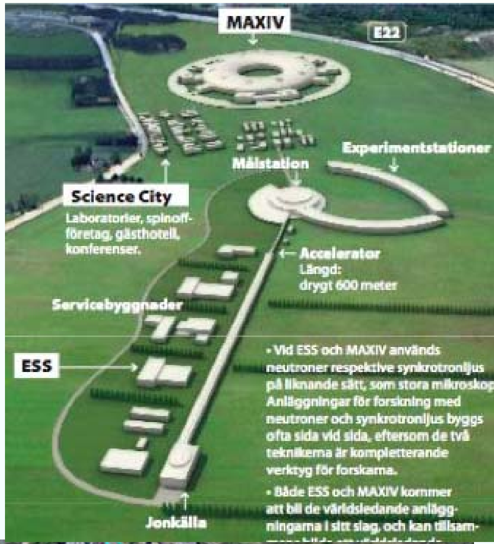
Graduate Training in Accel. Sci.

Since 2011

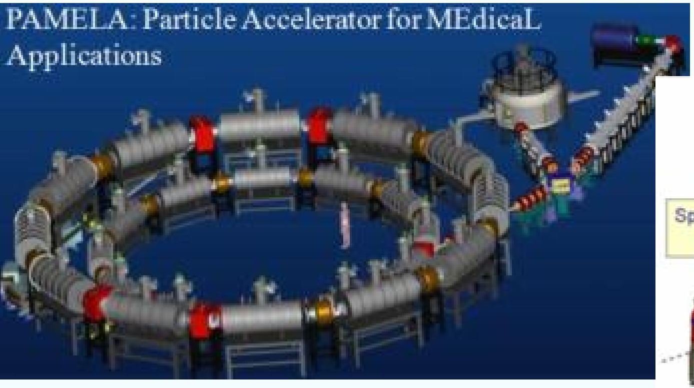
JAI directions: Enabling Acc. Techniques

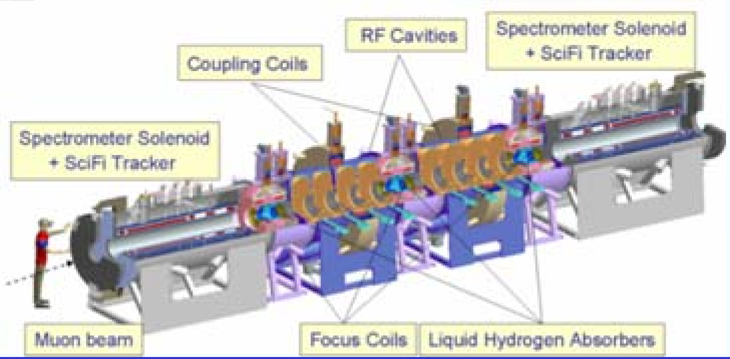
- 3rd Gen Light Sources
- Future 4th Gen Light Source design
- ISIS & ESS neutron sources
- Neutrino Factory / μ-cooling
- Accelerators for cancer therapy
- Ion sources
- LHC upgrade
- Linear Colliders





PTCRi

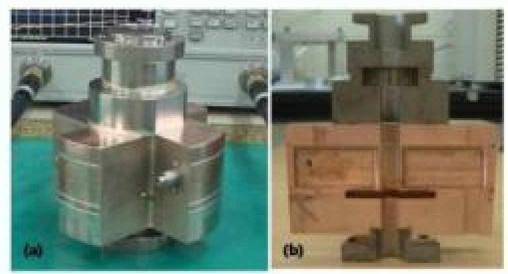




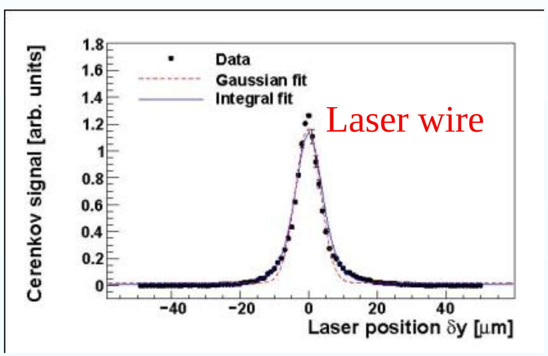
JAI directions: Advanced Beam Instrumentation

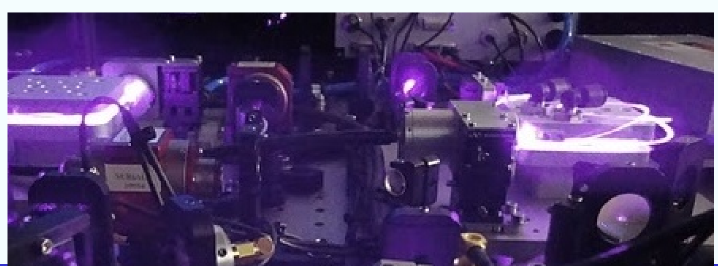
- **Far-Infrared Coherent Radiation**
  - CSR, CDR for beam diagnostics
  - Soft-X ray and microwave source based on Thomson scattering of CDR
- **Nano-resolution BPM**
  - C, S-band (~100nm resol.)
  - Special ~nm resolution
- **Coherent Smith-Purcell radiation**
  - Longitudinal diagnostics –extending to fs range
- **Laser – wire**
- **Ultra-fast nanosecond feedback**

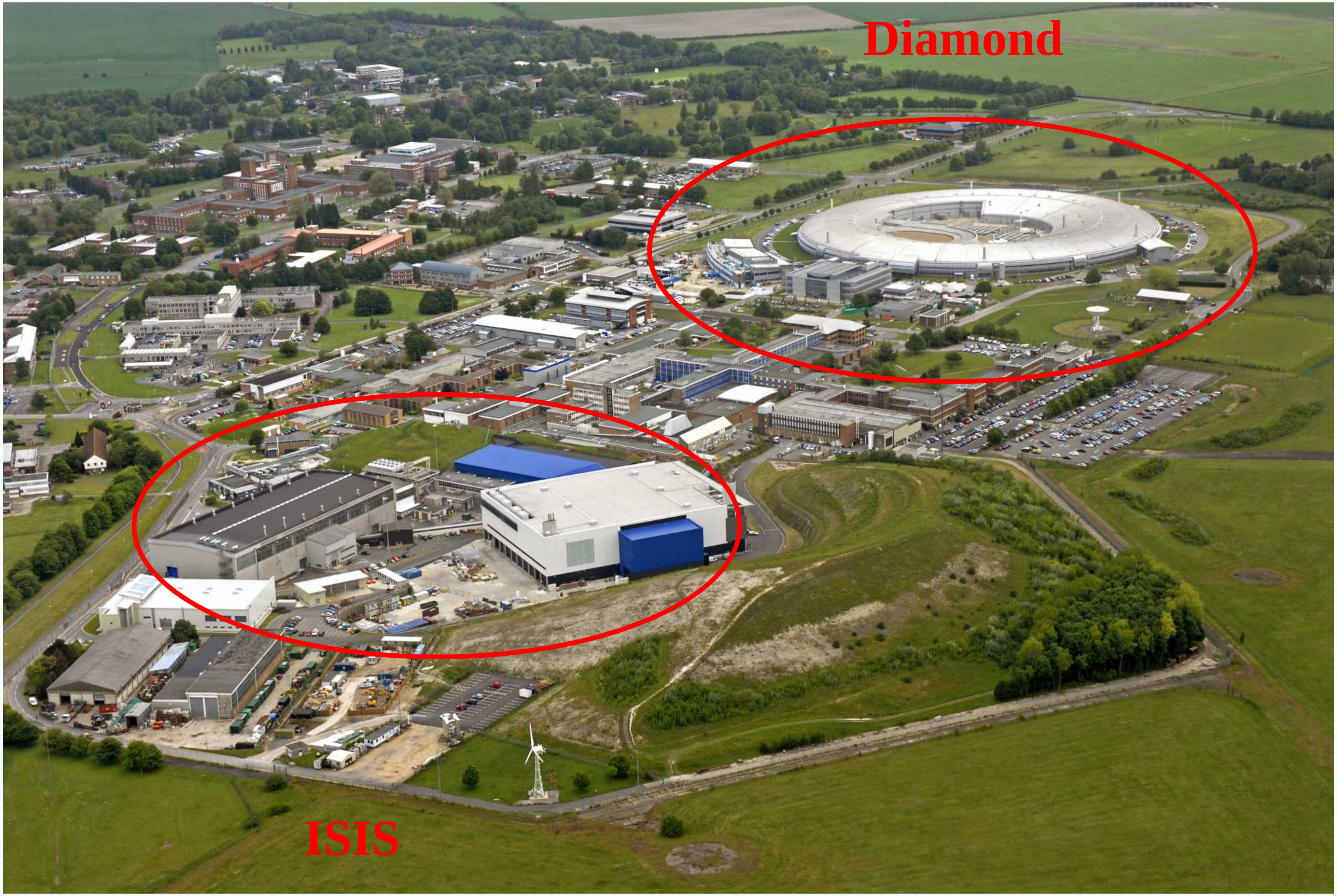
LUXC, jointly with KEK



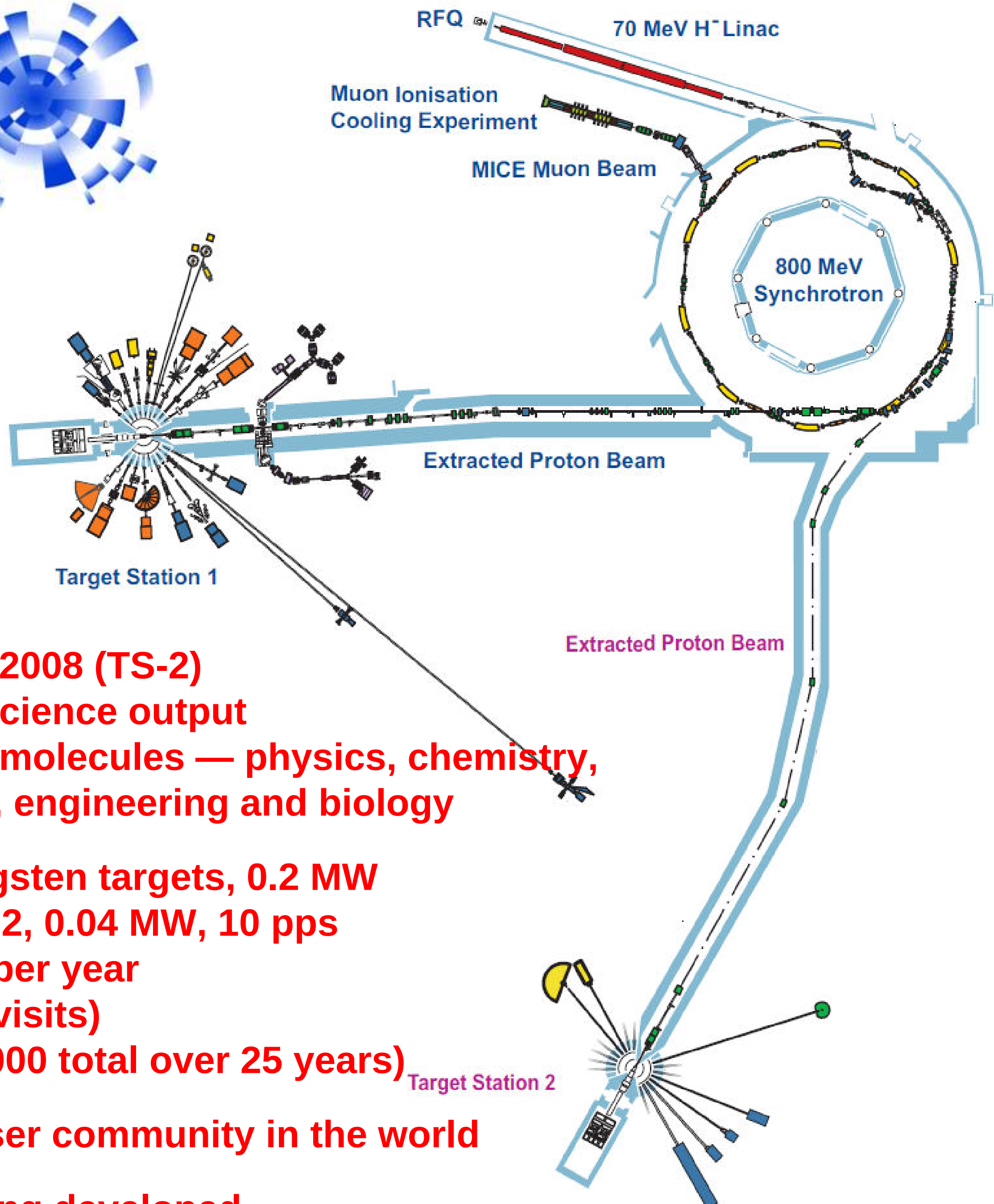
Smith-Purcell diagnostics instrumentation







Rutherford Appleton Laboratory, looking north-east



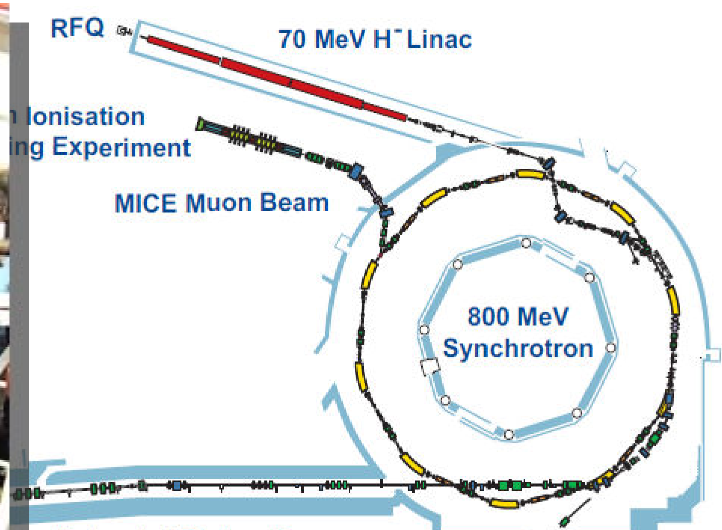
Spallation neutron source
First neutrons 1984 (TS-1), 2008 (TS-2)
World-leading in terms of science output
Structure and dynamics of molecules — physics, chemistry, materials science, geology, engineering and biology

800 MeV protons on to tungsten targets, 0.2 MW
TS-1, 0.16 MW, 40 pps; TS-2, 0.04 MW, 10 pps
~750 neutron experiments per year
~1500 visitors/year (~5000 visits)
~450 publications/year (~9000 total over 25 years)

UK: has largest neutron user community in the world

Upgrades to 1-5MW are being developed

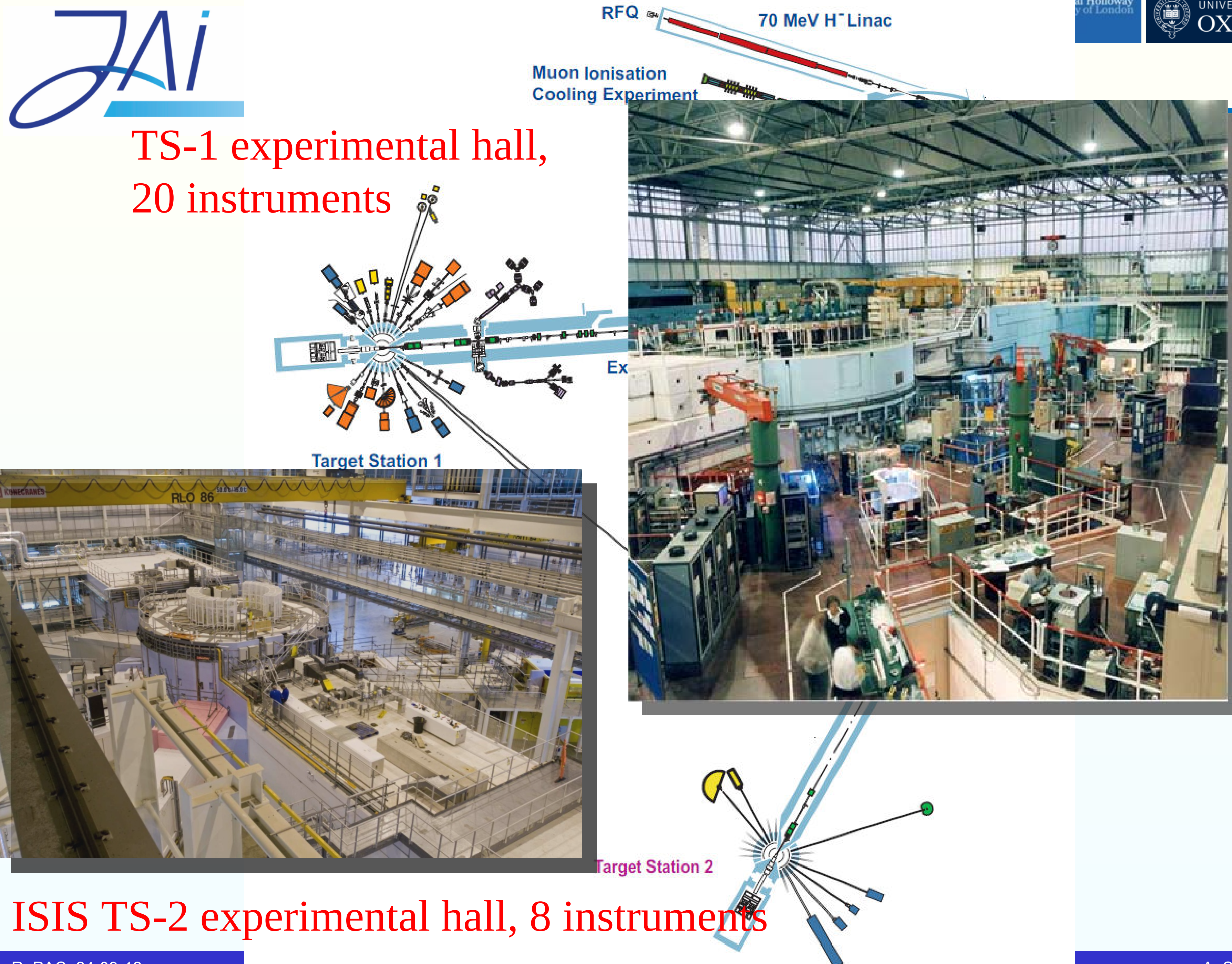
ISIS 70 MeV H⁻ linac



4-rod RFQ,
202 MHz
0.2 MW RF
pulsed

ISIS 800 MeV synchrotron

TS-1 experimental hall, 20 instruments



ISIS TS-2 experimental hall, 8 instruments

Diamond Light Source

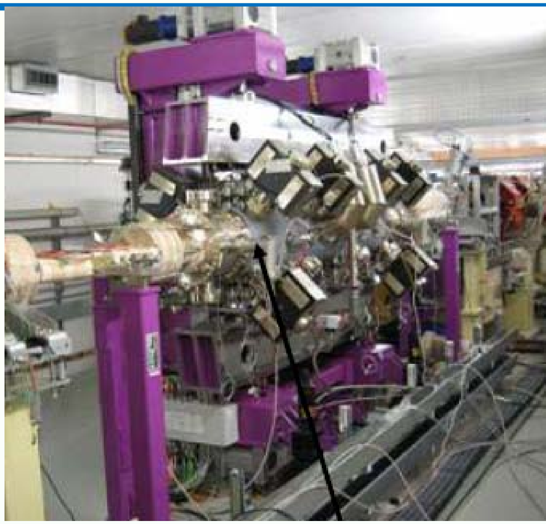
Diamond is a third generation light source open for users since January 2007

100 MeV LINAC; 3 GeV Booster; 3 GeV storage ring

2.7 nm emittance – 300 mA – 18 beamlines in operation (12 in-vacuum IDs)

3GeV Booster

100 MeV linac



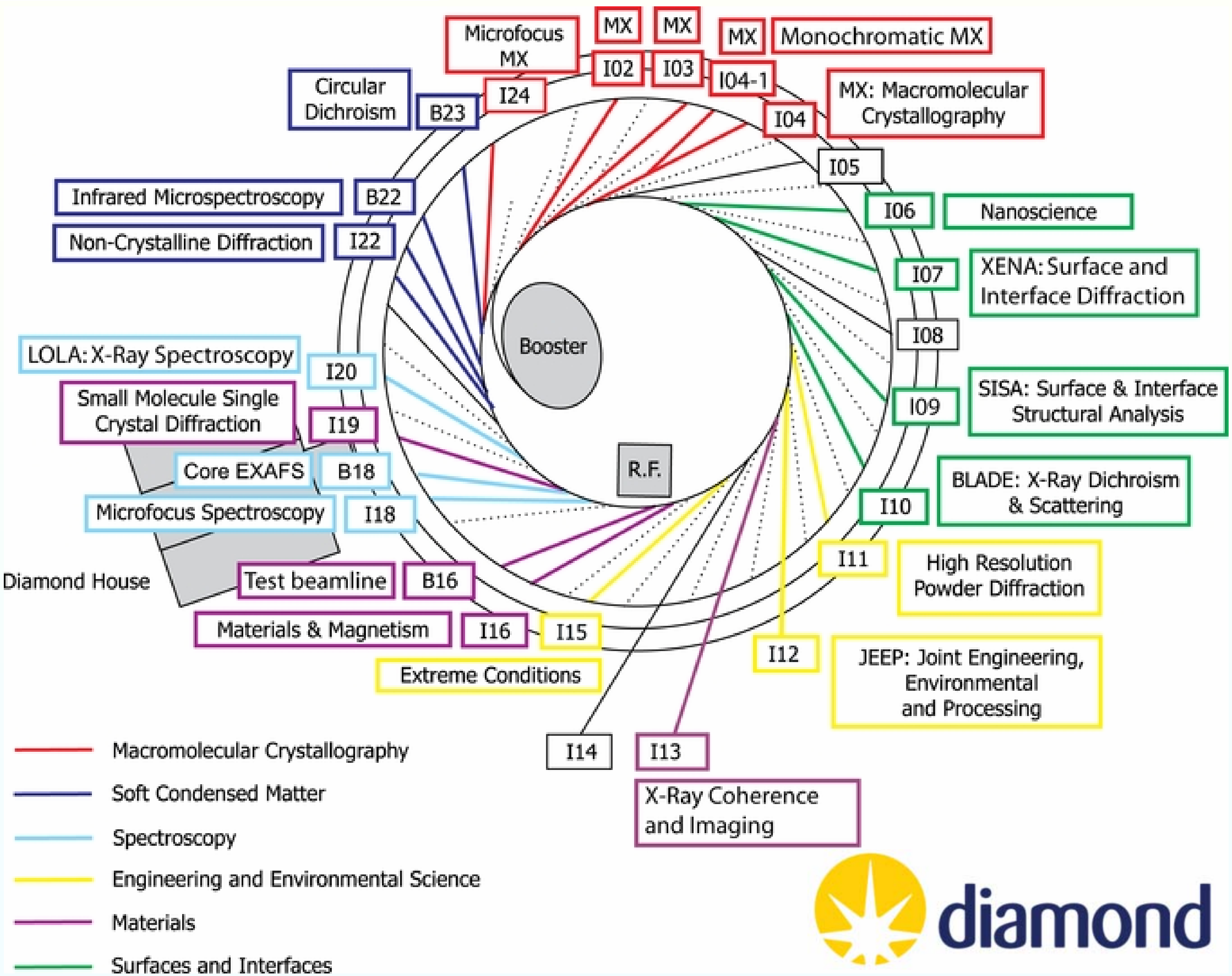
in-vacuum undulator

Storage Ring

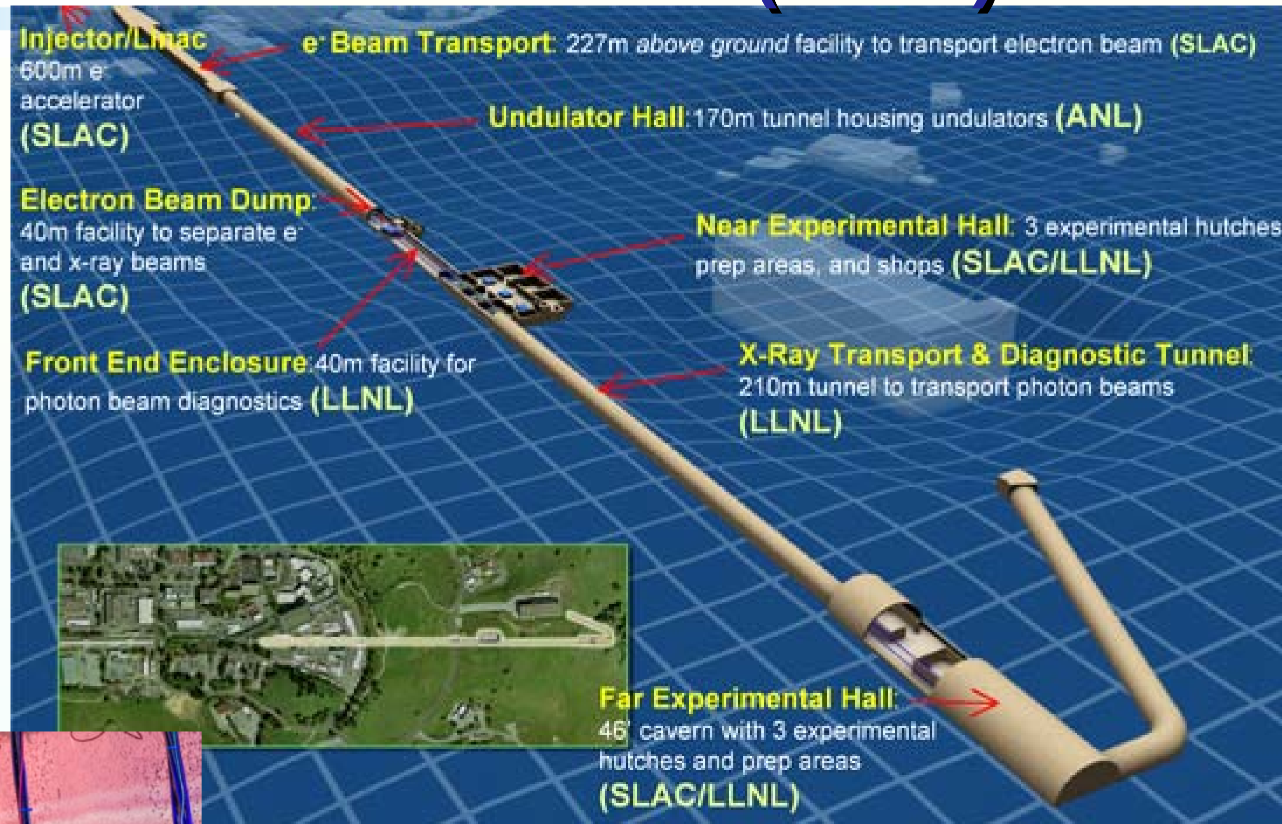
SC cavities (2)

SC wiggler

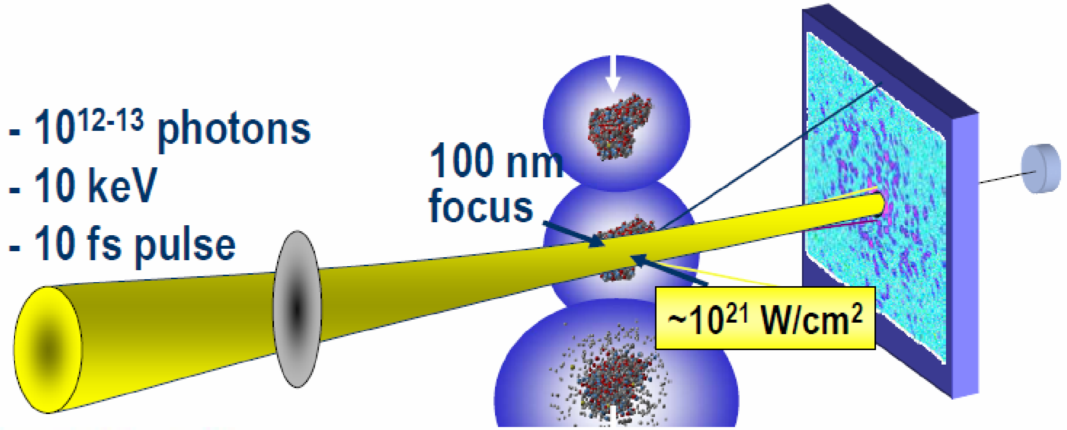
3rd Gen light source - Diamond

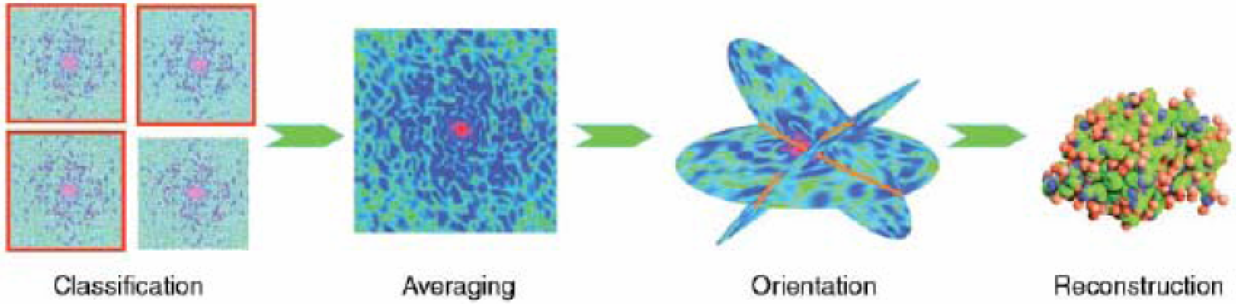


4^{th} Gen – FEL at SLAC (LCLS)

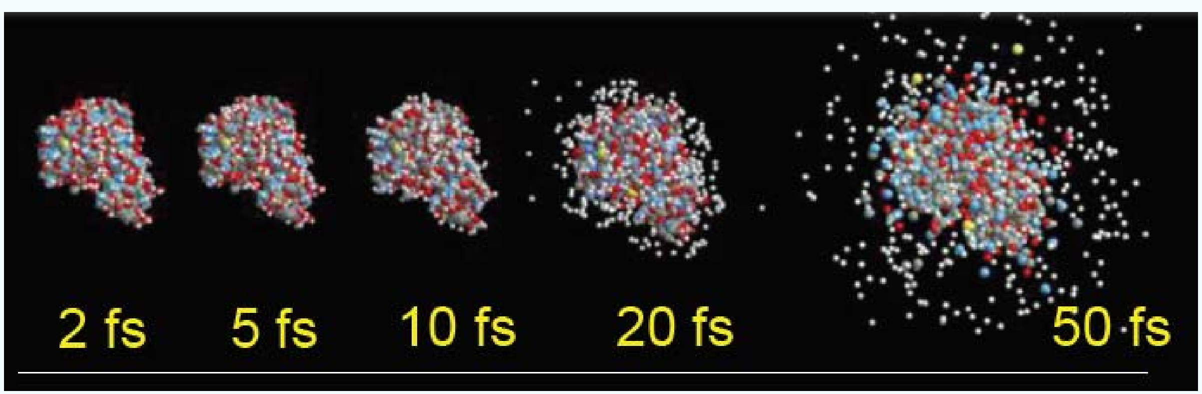


Coherent diffractive imaging of single particles





Calculations. in vacuum Neutze et al., Nature 2000 Chapman, Gaffney Science 2007



New Light Source

- Aim: measure structural dynamics in real time, i.e. to observe the motions of atoms and molecules as they undertake the fundamental changes that underpin physical, chemical and biological processes
- Free electron lasers (FELs) are the first tools that science has had that can offer both simultaneous nanoscopic spatial resolution and femtosecond temporal resolution
- The present operational and planned FEL facilities (e.g. FLASH (Hamburg), XFEL (Hamburg), LCLS (Stanford)) offer the first opportunities for that new science
- The current generation of FELs are, however, limited in the reproducibility of the X-ray pulses that they will produce and in the time structure of the pulse train
- To overcome these limits, and so to allow structural dynamics measurements in the femtosecond range to be fully realised, a New Light Source high repetition rate coherent FEL has been designed – a new class of machine which produces fully controlled X-ray pulses

New Light Source

Key science drivers:

•IMAGING NANOSCALE STRUCTURES.
•CAPTURING FLUCTUATING AND RAPIDLY EVOLVING SYSTEMS.
•STRUCTURAL DYNAMICS UNDERLYING PHYSICAL AND CHEMICAL CHANGES.
•ULTRA-FAST DYNAMICS IN MULTI-ELECTRON SYSTEMS.

Characteristics:

•Photon energies from THz to X-ray
•Short Pulses
•Full Coherence
•High Brightness
•High Repetition Rate

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NEW LIGHT SOURCE (NLS) PROJECT:
CONCEPTUAL DESIGN REPORT

NLS

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PROJECT MANAGER
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Justin Wark (Oxford) High Energy Density Science
Peter Weightman (Liverpool) Life Sciences
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May 2010

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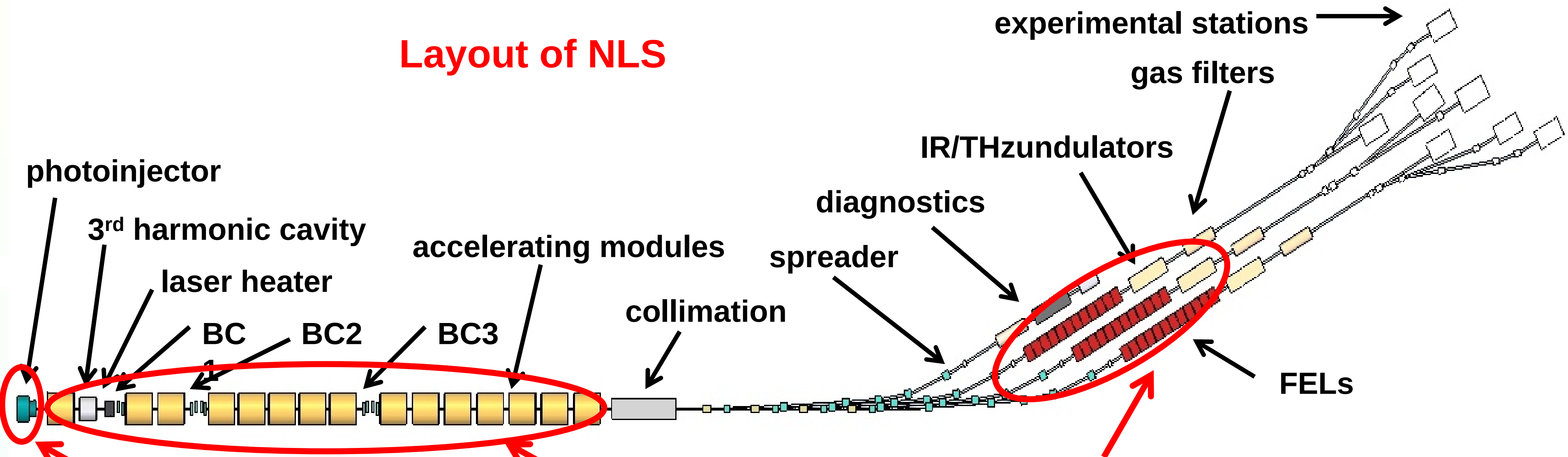
The New Light Source Project

Layout of NLS



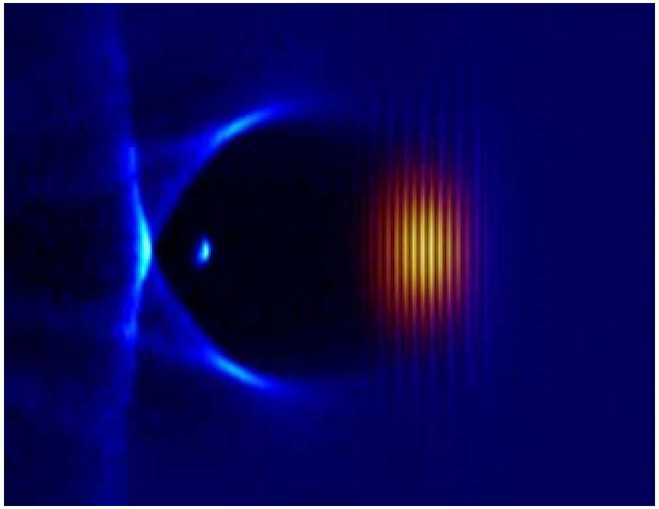
3 free-electron lasers covering the photon energy range 50 eV–1 keV,
- ***GW peak power***
- ***20 fs pulses***
- ***laser HHG seeded for longitudinal coherence***

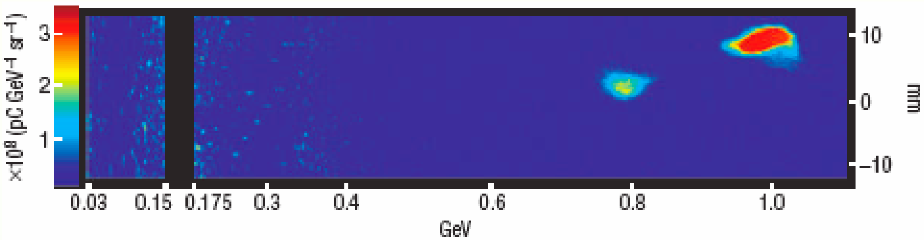
high brightness electron gun, operating (initially) at 1 kHz (upgradable to MHz)

2.25 GeV cw superconducting linac

CDR completed in May 2010

JAI directions: Laser-Plasma Acceleration





1GeV acceleration in just 3cm of plasma

W. Leemans, B. Nagler, A. Gonsalves, C. Toth, K. Nakamura, C. Geddes, E. Esarey, C. B.Schroeder, & S. Hooker, ***Nature Physics*** 2006

← Simulation of laser-plasma acceleration

Rapid progress in beam energy achieved with laser-plasma acceleration shows that the synergy of accelerators, laser and plasma is revolutionizing the field of accelerator science

→ Compact X-ray light sources based on laser-plasma accel^n

→ Aim to develop commercial applications

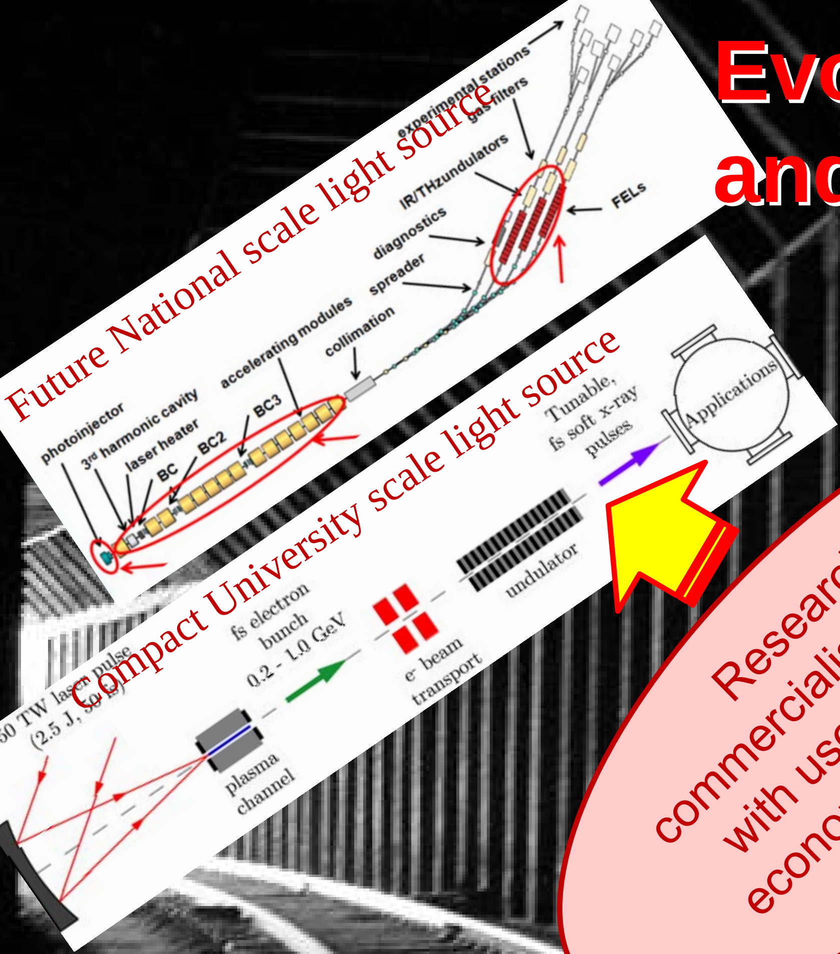
Project to be developed in collaboration with science centres in UK and worldwide

John Adams Institute
J.A.I.
for Accelerator Science

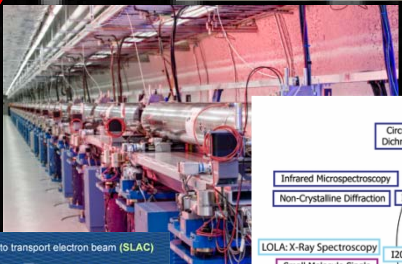
Evolution of computers and light sources

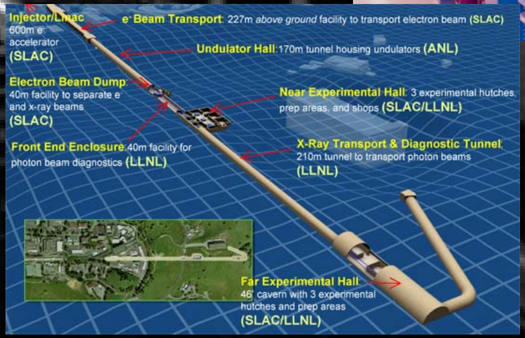
"IBM bringing out a personal computer would be like teaching an elephant to tap dance" cca. 1981

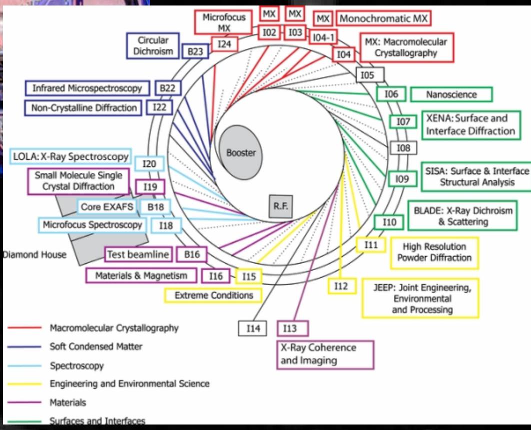
Evolution of computers and light sources



Research, commercialisation, work with users, industry, economists, to change the paradigm







CHALLENGE FOR ACCELERATOR SCIENCE

Factor of 1000X:

Energy –up

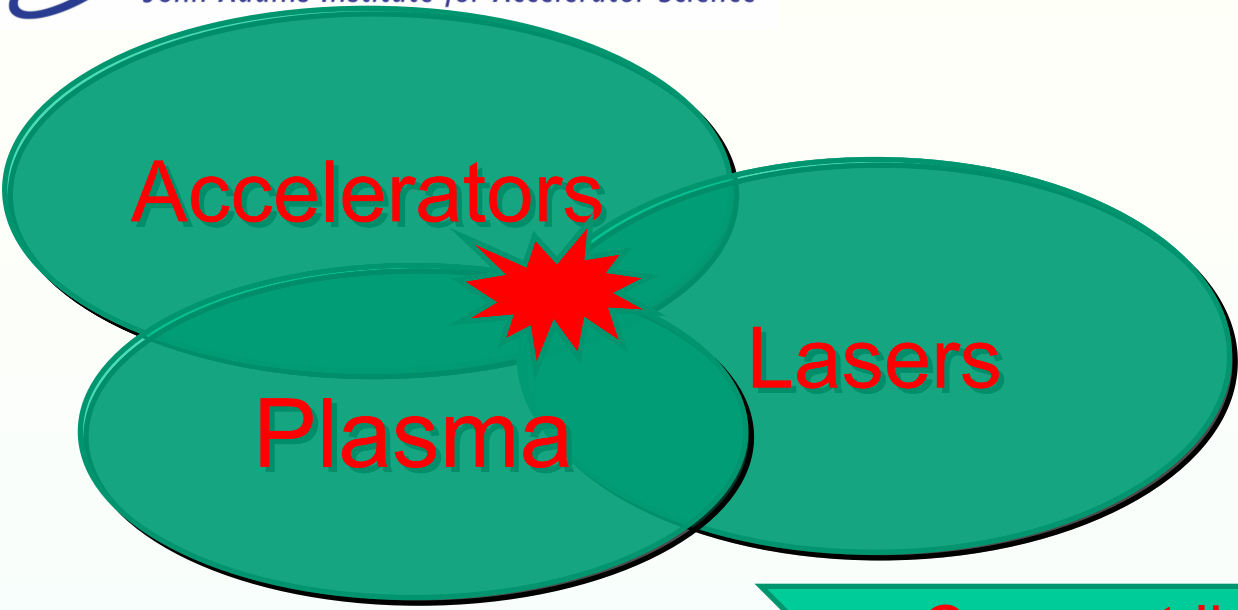
Power-up

Faster timing

Finer resolution

=> Not evolution, but revolution

Atsuto Suzuki (KEK), chair of ICFA (International Committee for Future Accelerators)

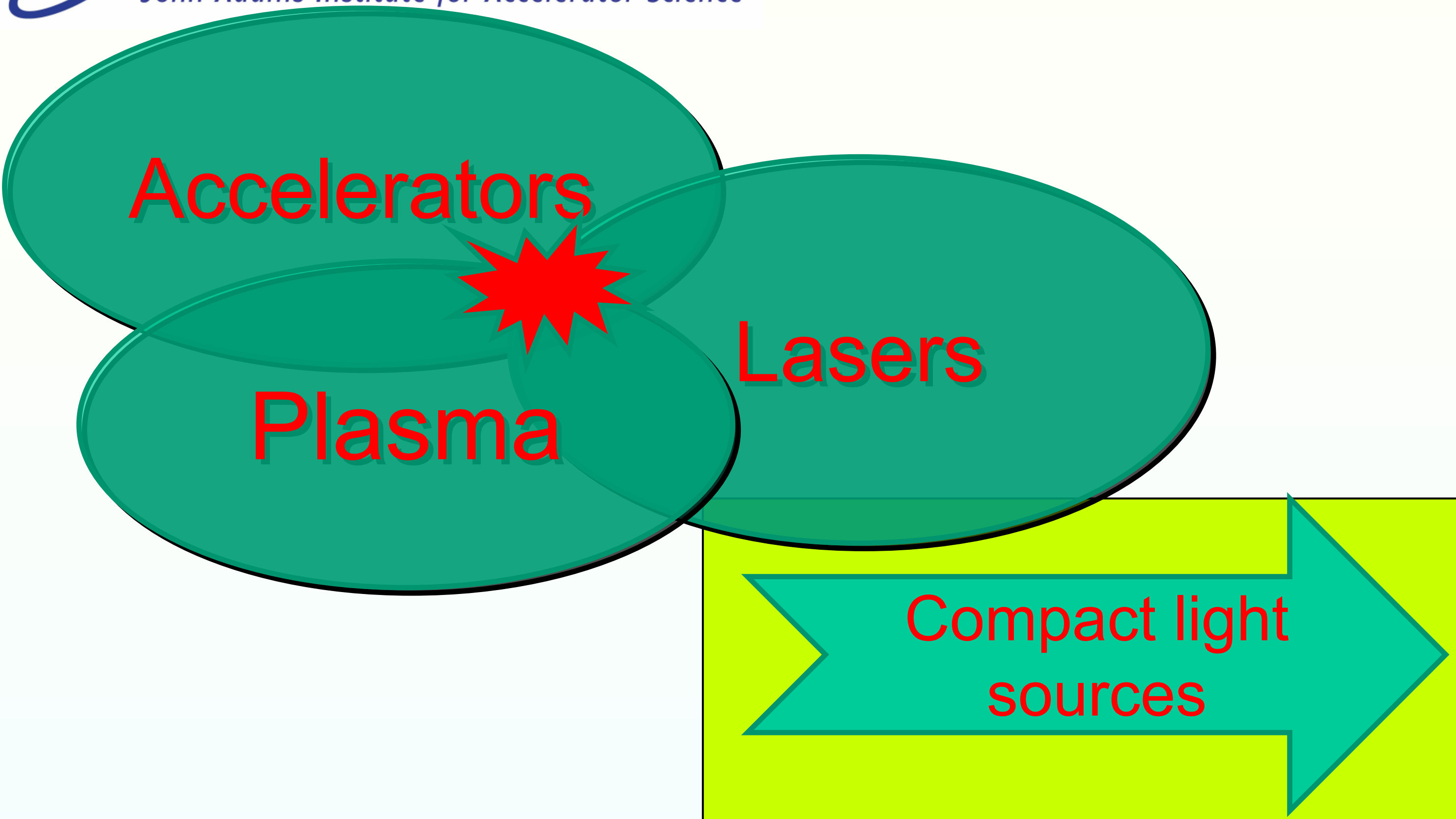


Compact light sources

Impact on society within ~5 years

HEP discovery machines

HEP applications in ~20 yrs or more



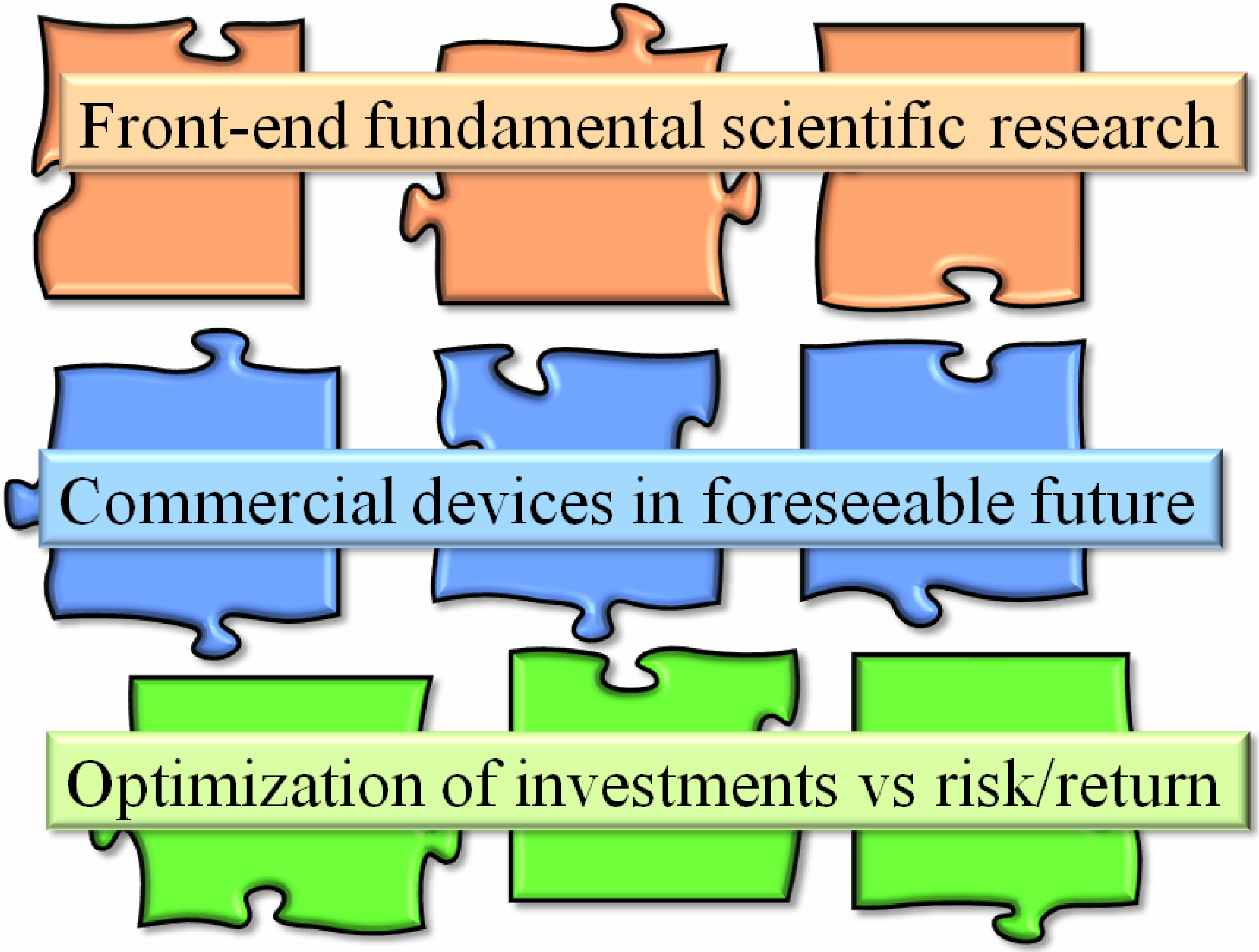
a) *Compton light sources*
b) *SRF based sources*
c) *Laser-Plasma light sources*

"Valley of Death"

- *A well known challenge – to bring scientific results to industry*
- *A gap between science result and technological innovation*
- *This challenge is often referred to "crossing the "Valley of Death"*

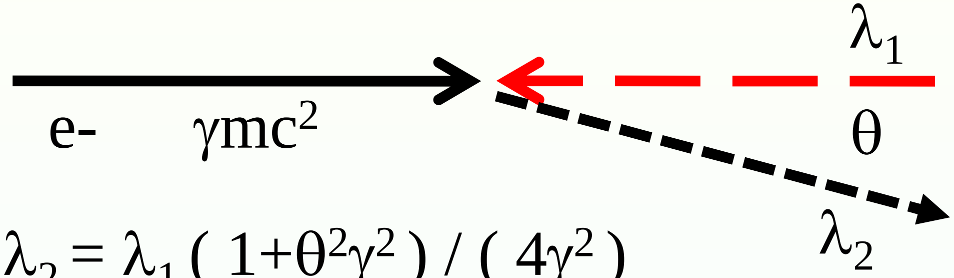
PS Public Service Review, UK Science and Technology, issue 04 www.publicservice.co.uk

Academia-Industry-Investor puzzle

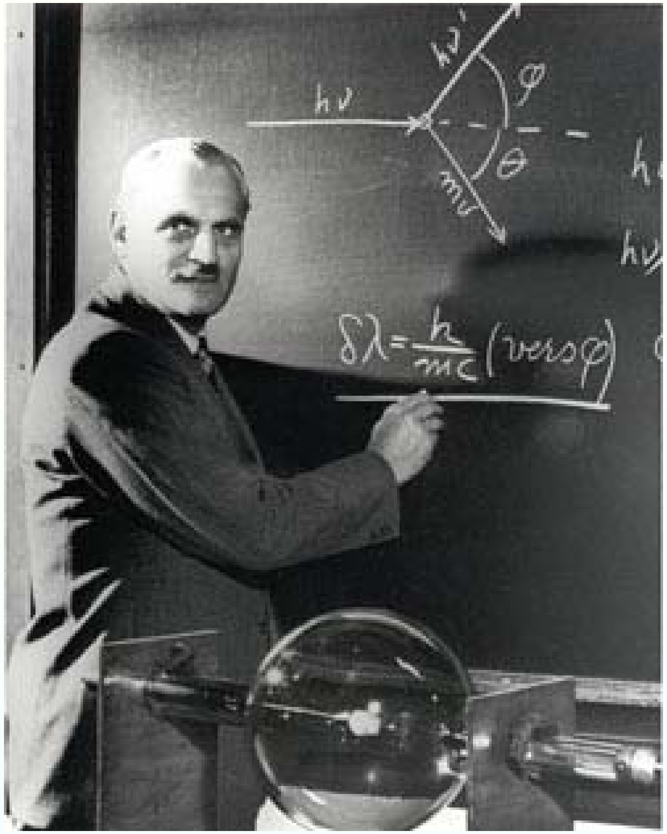


Compton scattering

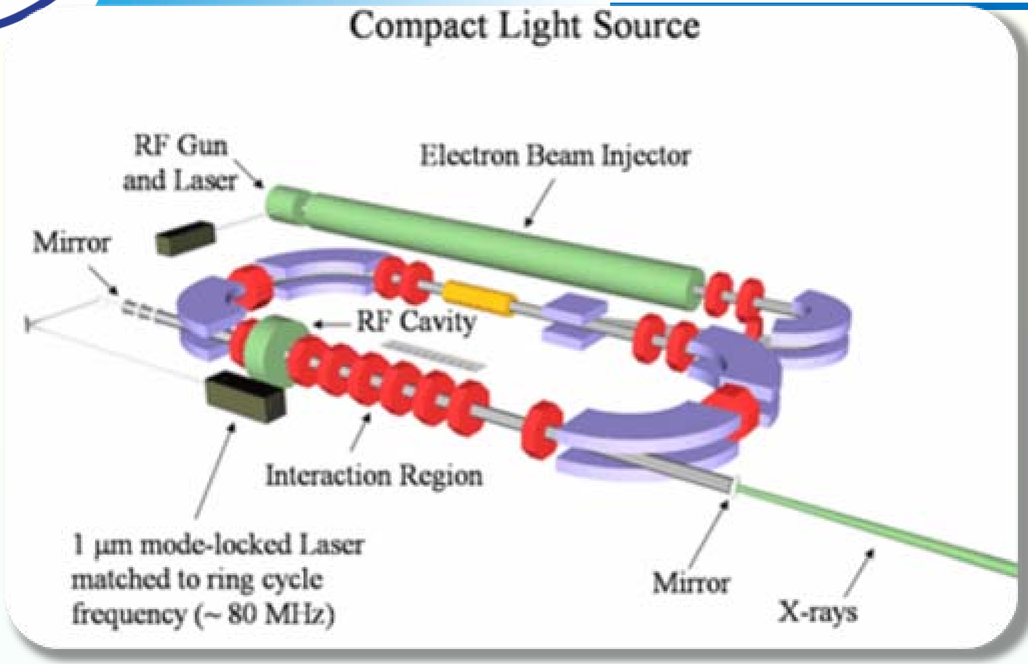
Inverse Compton scattering:
photon gains energy after interaction

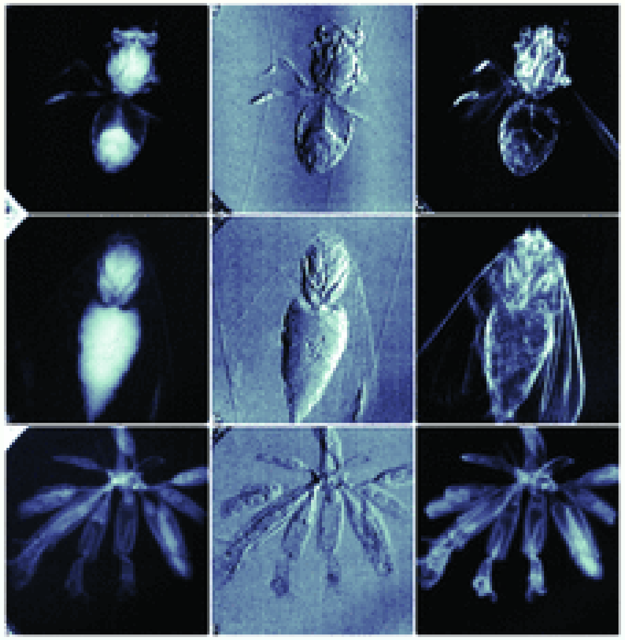


$$\lambda_2 = \lambda_1 (1+\theta^2\gamma^2) / (4\gamma^2)$$



- **Examples for λ_1= 532 nm (2.33 eV)**
  - **e- 5.11 MeV (γ =10), λ_2= 1.33 nm (0.93 keV)**
  - **e- 18.6 MeV (γ =36.5), λ_2= 0.1 nm (12.4 keV)**

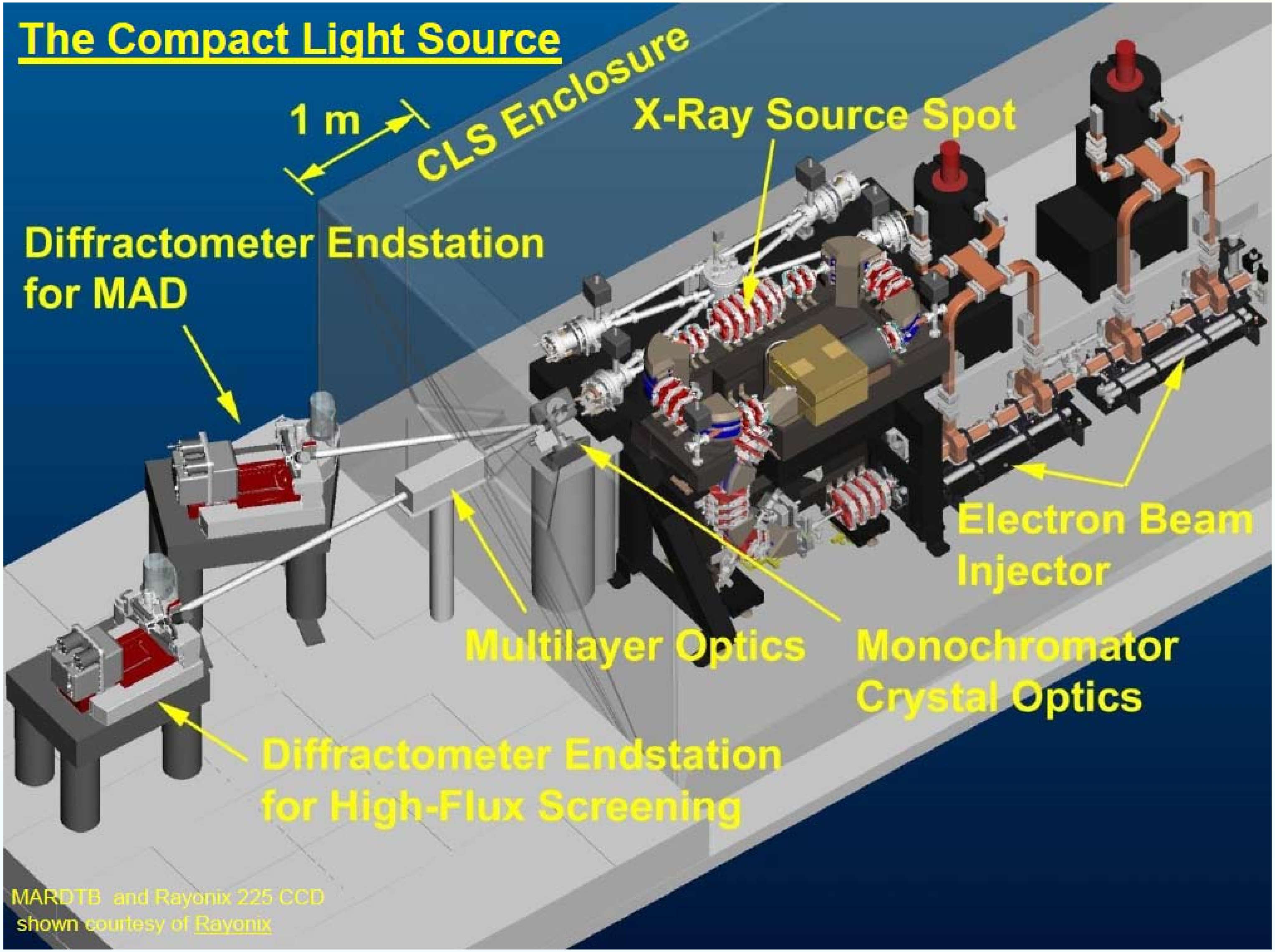




Hard X-ray phase-contrast imaging with the Compact Light Source based on inverse Compton X-rays, M. Bech, O. Bunk, C. David, R. Ruth, J. Rifkin, R. Loewen, R. Feidenhans'l and F. Pfeiffer et al, *J. Synchrotron Rad.* (2009). **16**, 43-47

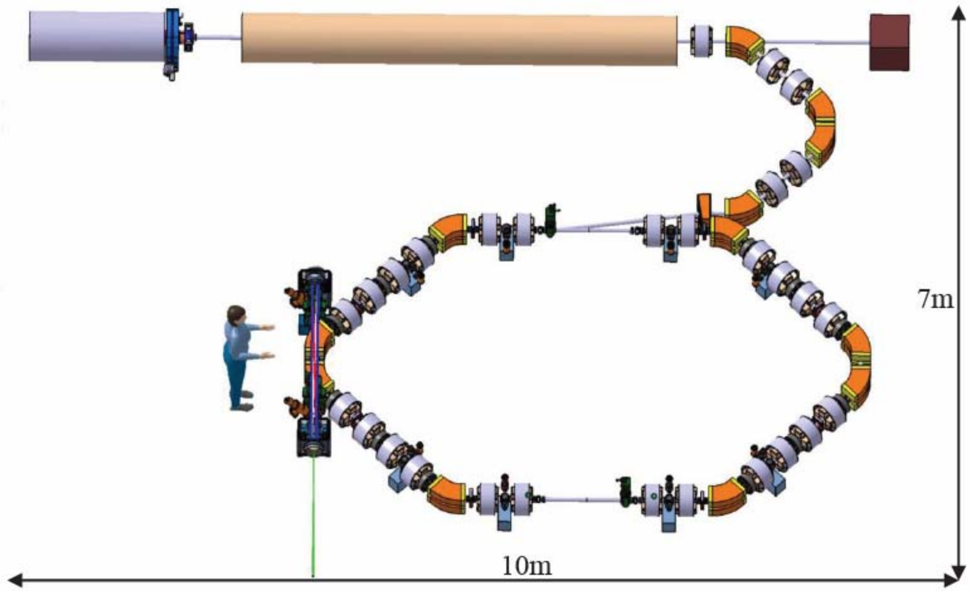
Lyncean Technologies, Inc.
Compact X-ray light source

25 MeV accelerator
X-ray tuneable from a few keV up to 35 keV
Fits in a 10x25 ft room
Clinical High Resolution Imaging System
Micro-tomography
Protein crystallography



R. Ruth, SLAC / Lyncean Technologies

THOM-X Compton source



X-ray energy 50-90 keV

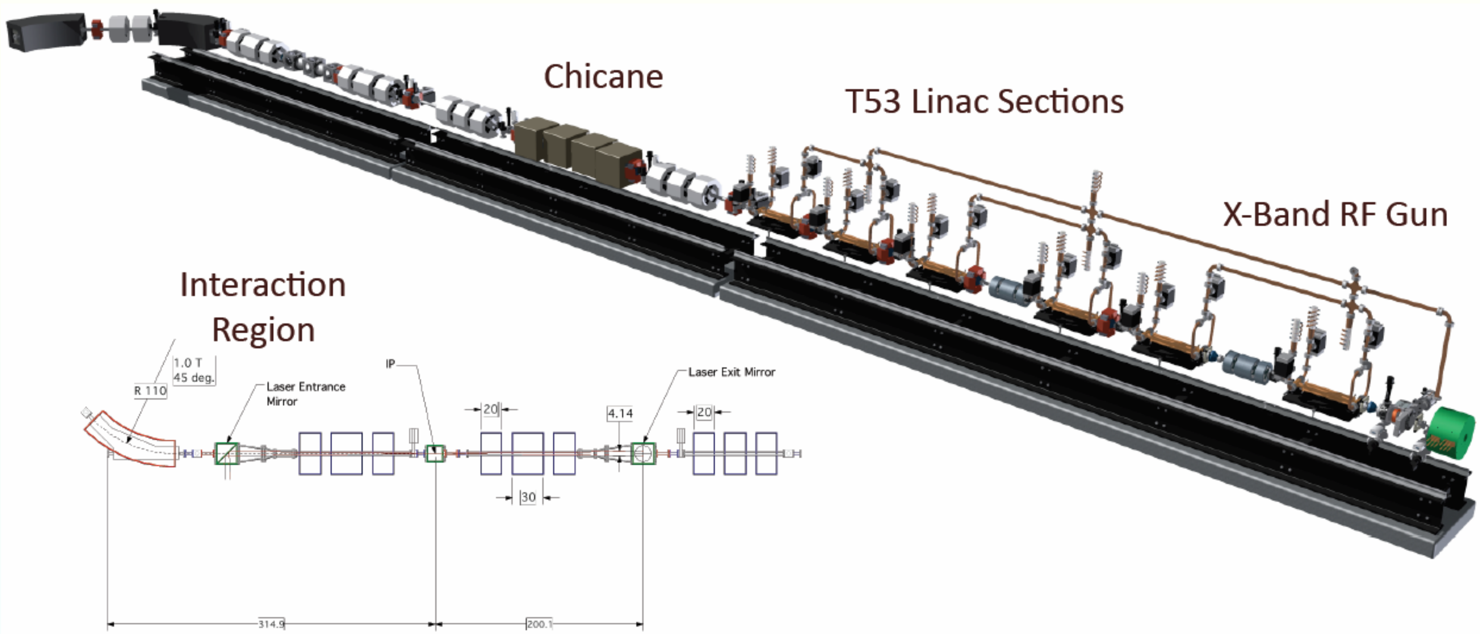
Flux 1E11-1E13 ph/s

Ring energy 50 MeV

A.Variola, A.Loulergue, F.Zomer, LAL RT 09/28, SOLEIL/SOU-RA-2678, 2010

- Scientific case
  - Cultural heritage application
  - Bio-Medical applications
  - X-ray crystallography

Mono-Energetic Gamma-Ray (MEGa-Ray) Compton light source (LLNL & SLAC)



Nuclear resonance fluorescence
Isotopic sensitivity

F.V. Hartemann (LLNL) et al, ICFA FLS 2010

- RF gun: 5.59 cells, 11.424 GHz, 200 MV/m
- Photocathode laser: Fiber-based, 4th harmonic, 50 uJ
- Linac: 250 MeV, 11.424 GHz, > 75 MV/m
- Interaction laser: 0.5 J, 1.064 nm, 10 ps; 0.1 J, 2ω
- Nominal rep. rate: 60-120 Hz
- Dose: 10^7-10^8/shot
- Flux: 10^{10}/s
- Energy range: 0.5 – 2.2 MeV
- Spectral bandwidth: 0.5%

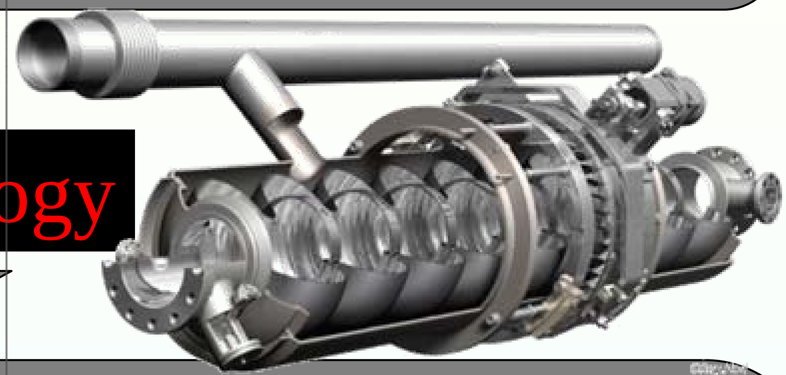
Compact (less than 10m) quasi-monochromatic (less than 1%)

High Flux (100 times than Compact normal Linac X-ray：10^{11} photons/sec 1% b.w.)

High Brightness (10^{17} photons/sec mrad^2 mm^2 0.1% b.w.)

Ultra-short pulse X-ray (40 fs ~)

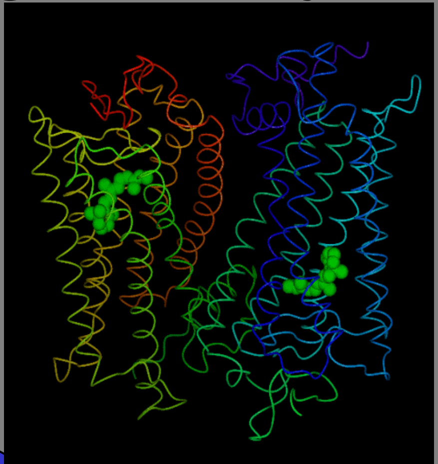
Quantum beam project



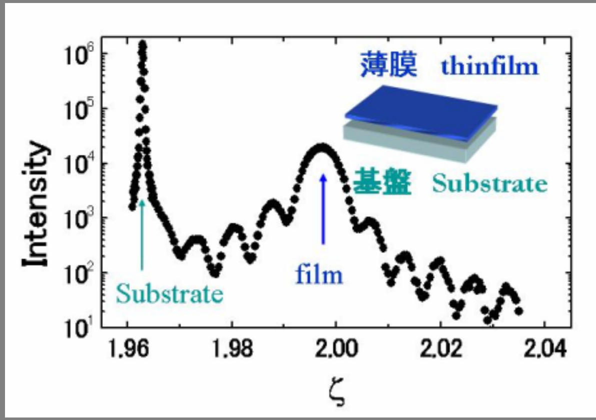
J. Urakawa, Quantum Beam Project

SCRF acceleration technology

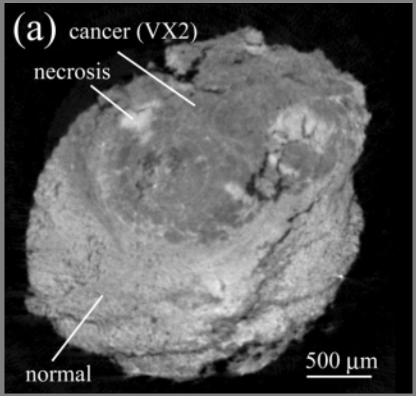
Structural genetic analysis,



Nano-material evaluation,



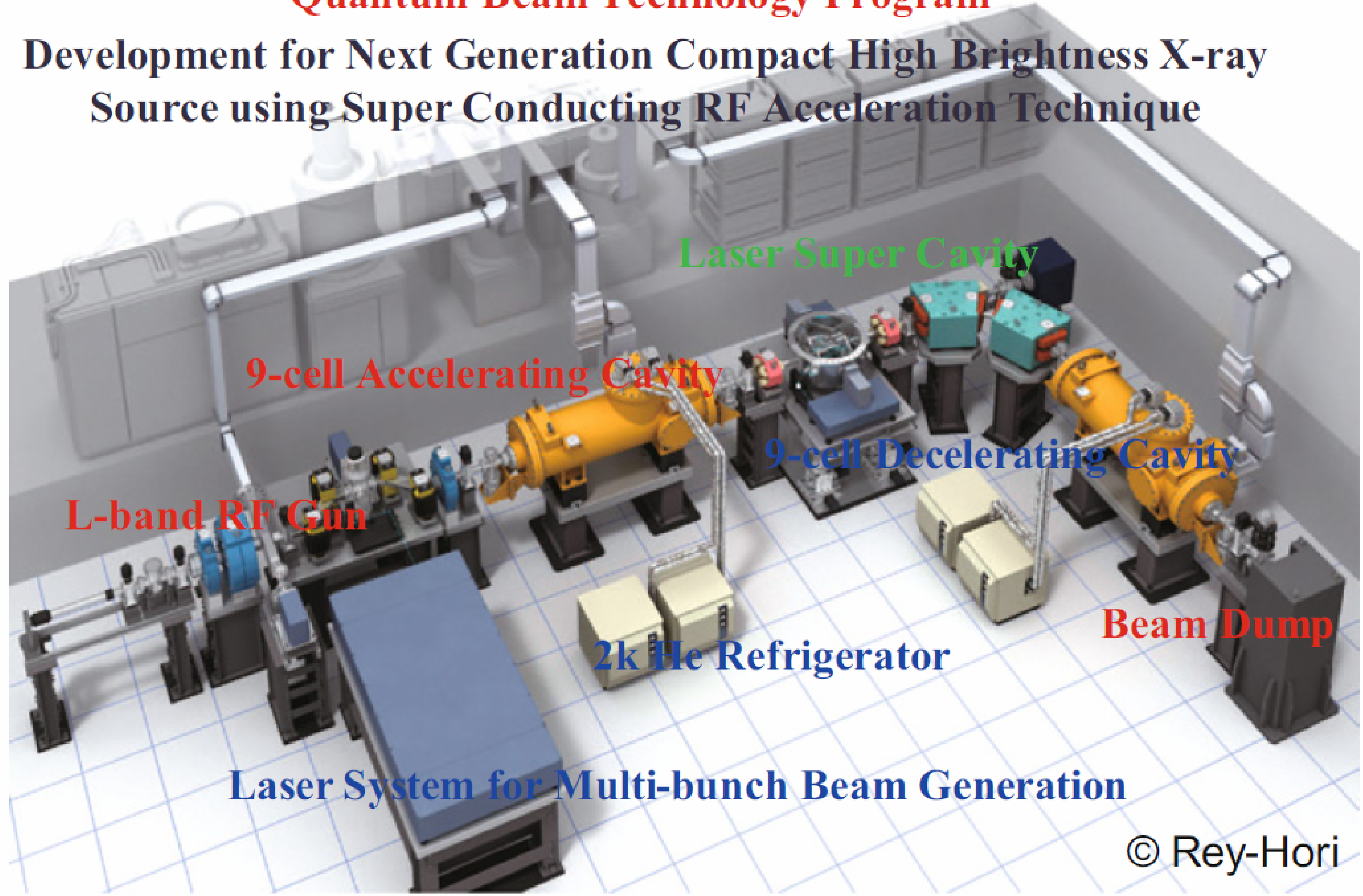
Highly fine X-ray Imaging



http://mml.k.u-tokyo.ac.jp/

Quantum Beam Technology Program

Development for Next Generation Compact High Brightness X-ray Source using Super Conducting RF Acceleration Technique



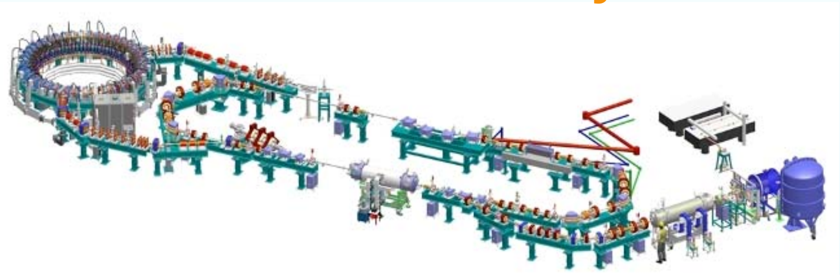
J. Urakawa, Nucl. Instr. and Meth. A (2010), doi:10.1016/j.nima.2010.02.019

Novel Compton Source

- **JAI & ASTeC plan to develop new compact X-ray source**
  - Based on a patent filed by JAI
  - Will use SC RF, sophisticated cryostat, sophisticated cavities
  - ASTeC experience match perfectly the needs of the project
  - Now forming working teams to develop the design further

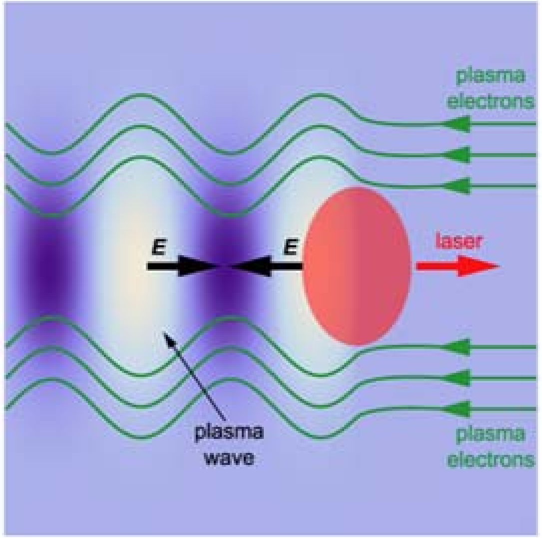
JAI
RAL

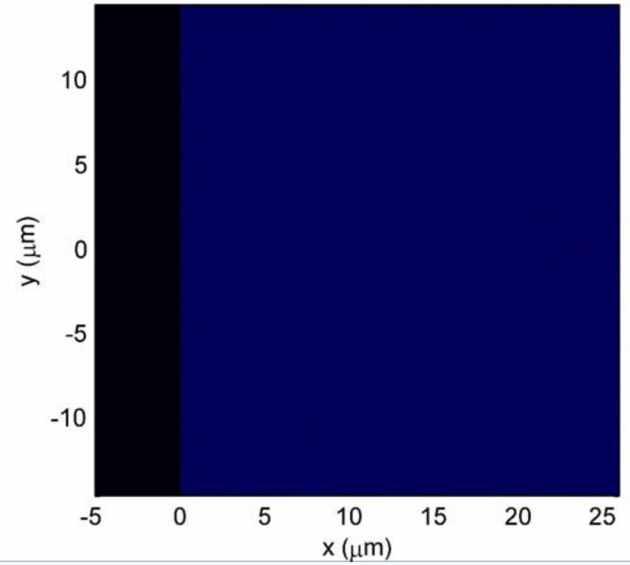
ASTeC & CI
Daresbury



Laser-Driven Plasma Accelerators

- Ponderomotive force of short (50fs), intense (10^{18} W cm^{-2}) laser pulse expels plasma electrons
- This sets up plasma wave which trails laser pulse
- Electric fields within plasma wave of order 100 GV/m formed
- 3 to 4 orders of magnitude bigger than in conventional accelerator!





Next several slides courtesy
Prof. Simon Hooker

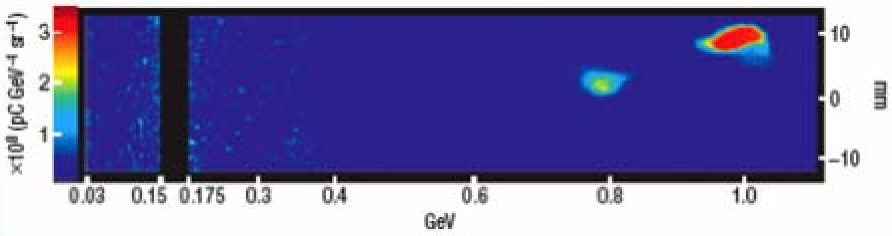
Rapid progress is being made …

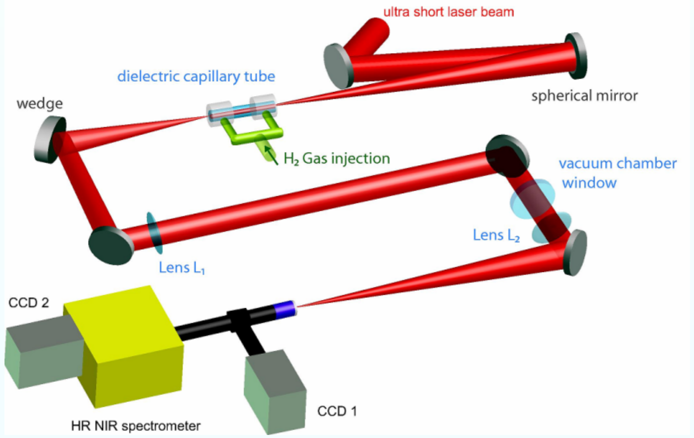
- 2004: First quasi-monoenergetic beams generated (IC, LBNL, LOA)
- 2006 First GeV beams generated (Oxford & LBNL)
- 2008 Generation of visible radiation in undulator (Strathclyde & Jena)
- 2009 Measurement of $E_z L$ ~ 1 GeV in weakly nonlinear regime (LPGP, Strathclyde, Lund, JIHT)
- 2009: Generation of extreme UV radiation in undulator (MPQ & Oxford)
- 2011: Biological imaging with betatron radiation (IC, Michigan & MPQ)


The light fantastic

Long division

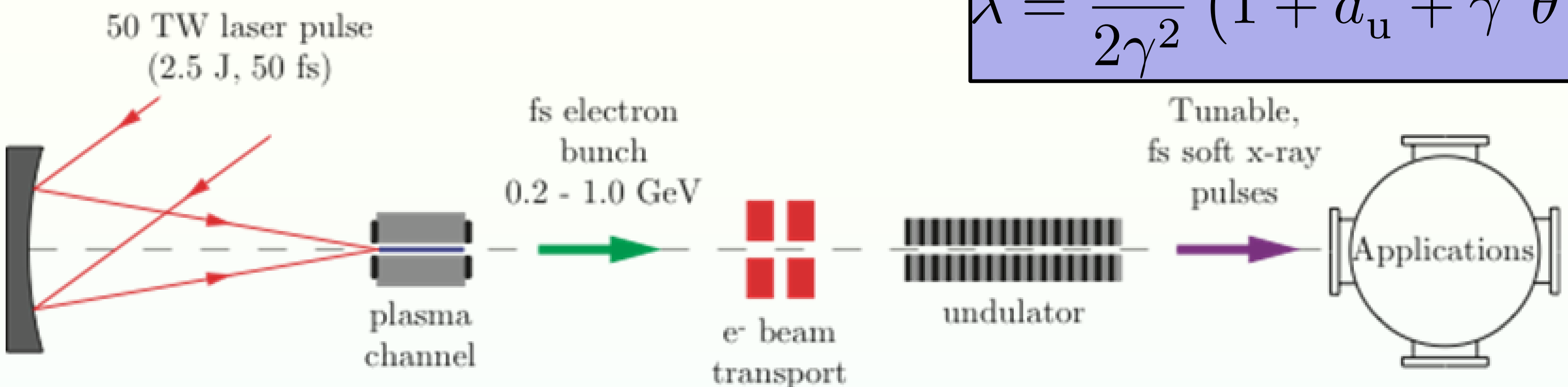
The Economist



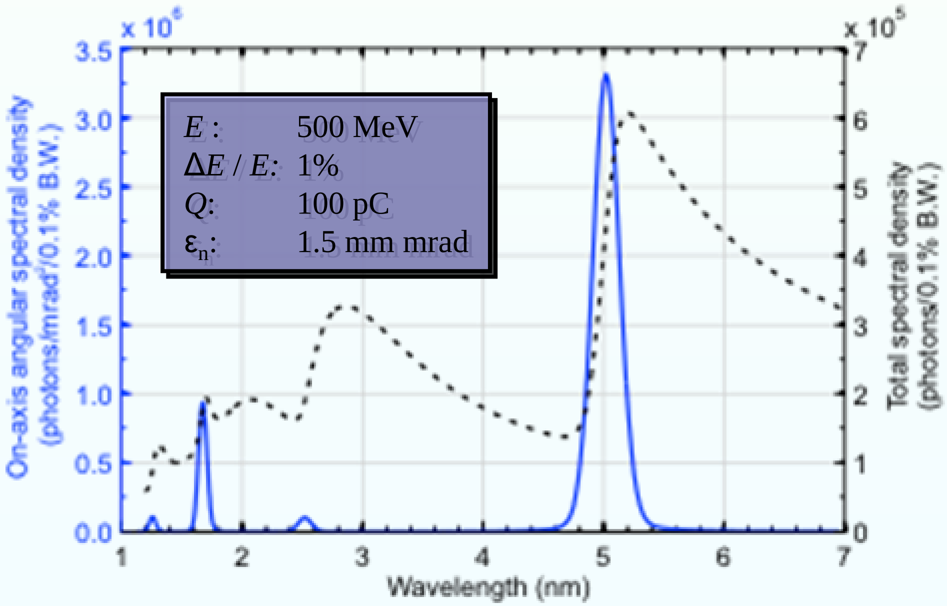


Compact radiation sources

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

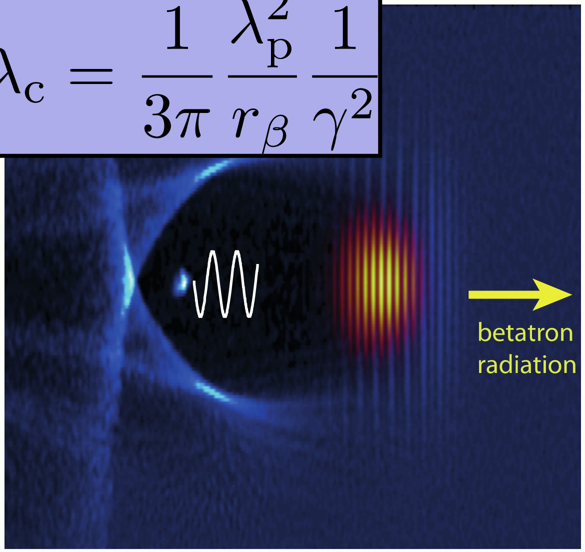


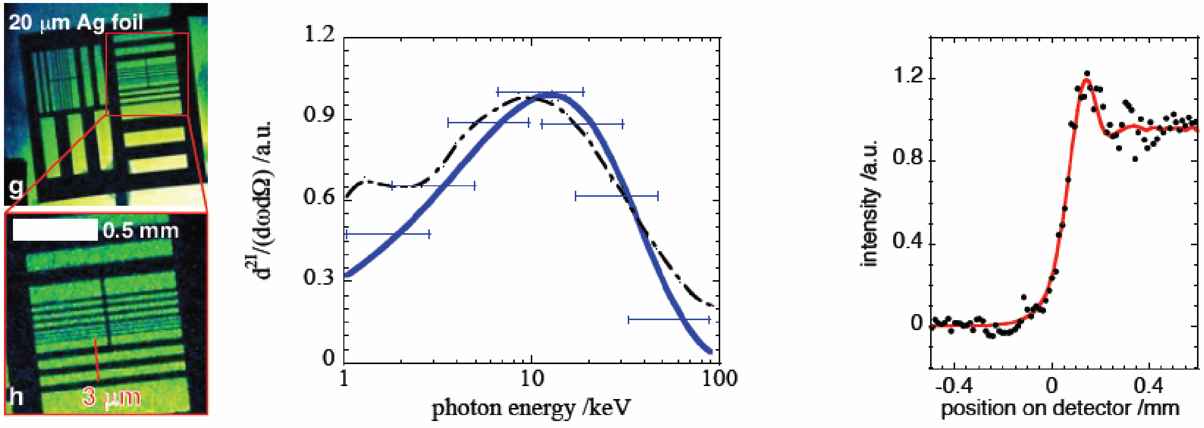
- Laser-driven plasma accelerators can already generate e-beams with:
  - Energy ~ 1 GeV
  - Bunch duration < 10 fs
  - Charge ~ 10 – 100 pC
- Ideal for driving compact radiation sources!
- Synchronized e-beams, soft x-rays & visible laser pulses – a powerful tool for time-resolved science



Betatron radiation sources

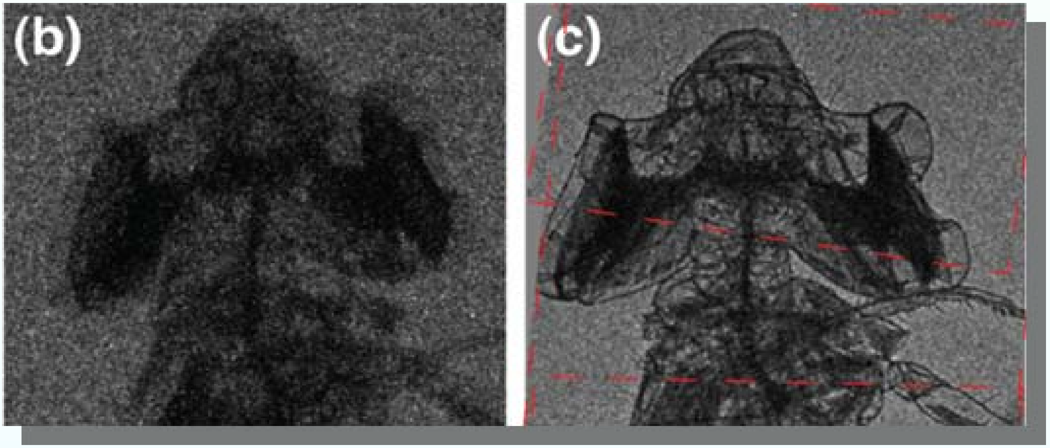
$$\lambda_c = \frac{1}{3\pi}\frac{\lambda_p^2}{r_\beta}\frac{1}{\gamma^2}$$



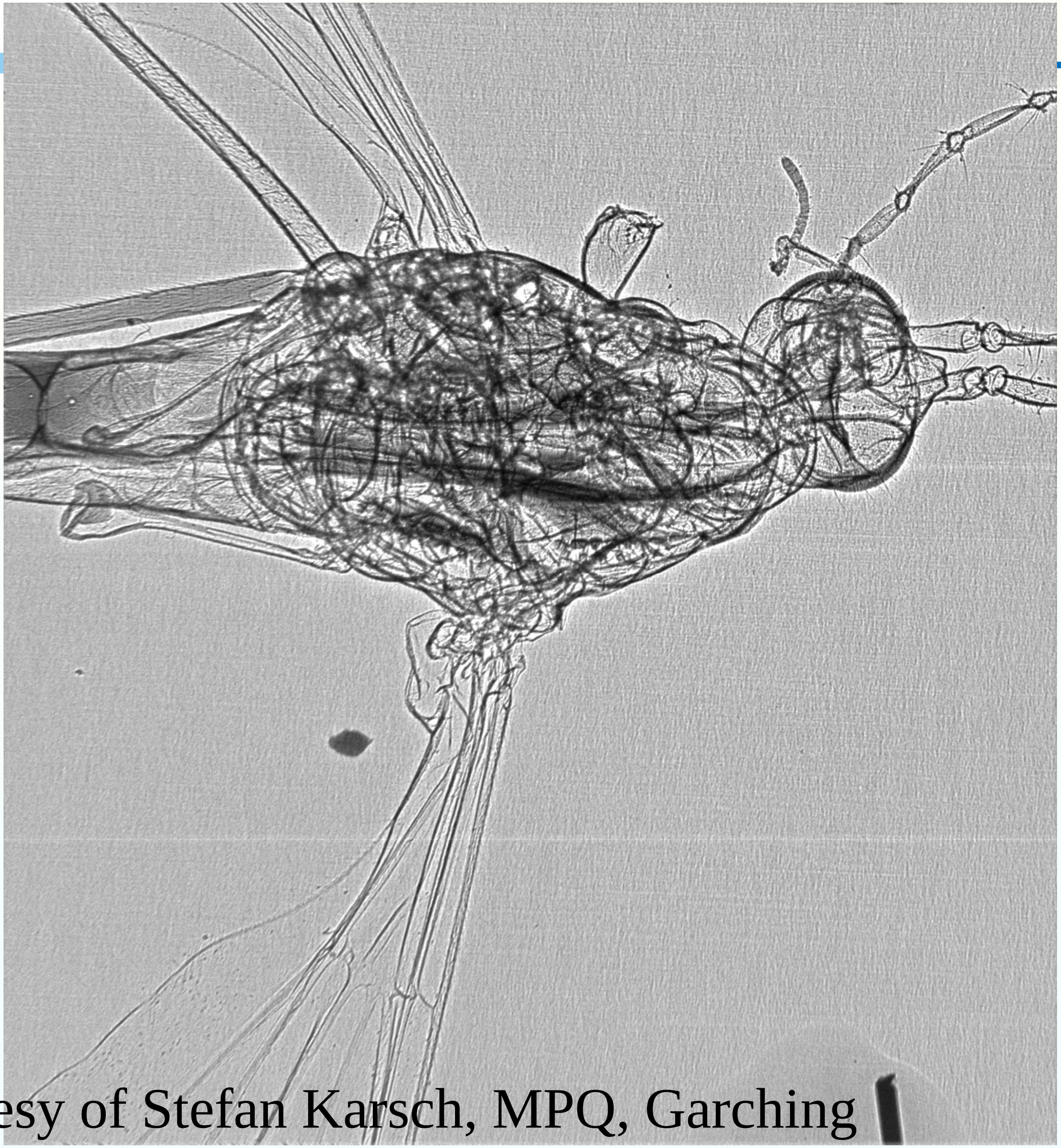


Imperial College /Michigan groups: Kneip Nature Phys 2010

- Strong radial electric field within plasma wave cause transverse oscillation of electron bunch
- Generates very bright **betatron radiation** in 1- 100 keV range

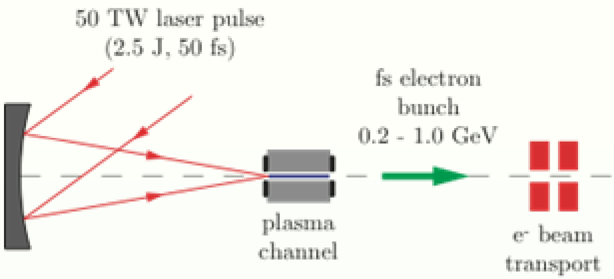


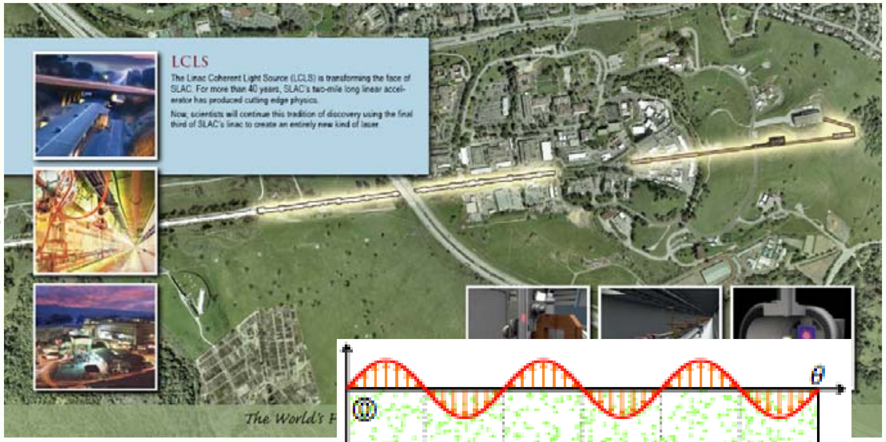
S. Kneip et al., Appl. Phys. Lett. **99, 093701 (2011)**

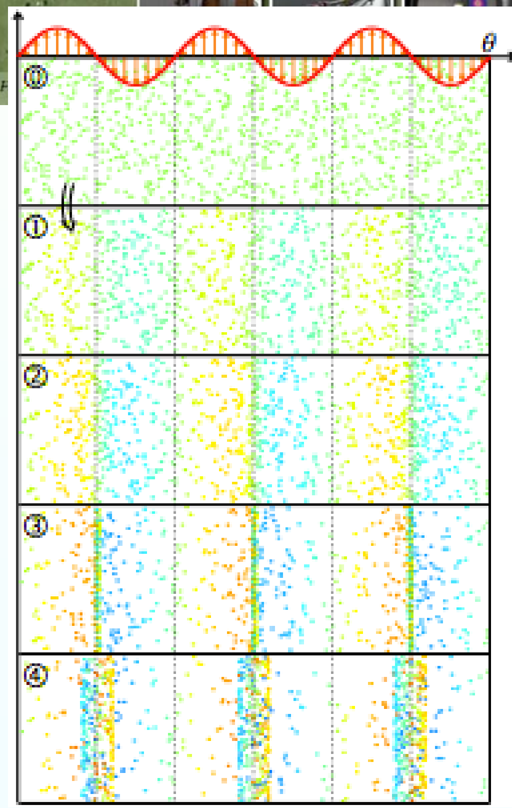


Courtesy of Stefan Karsch, MPQ, Garching

Compact FELs







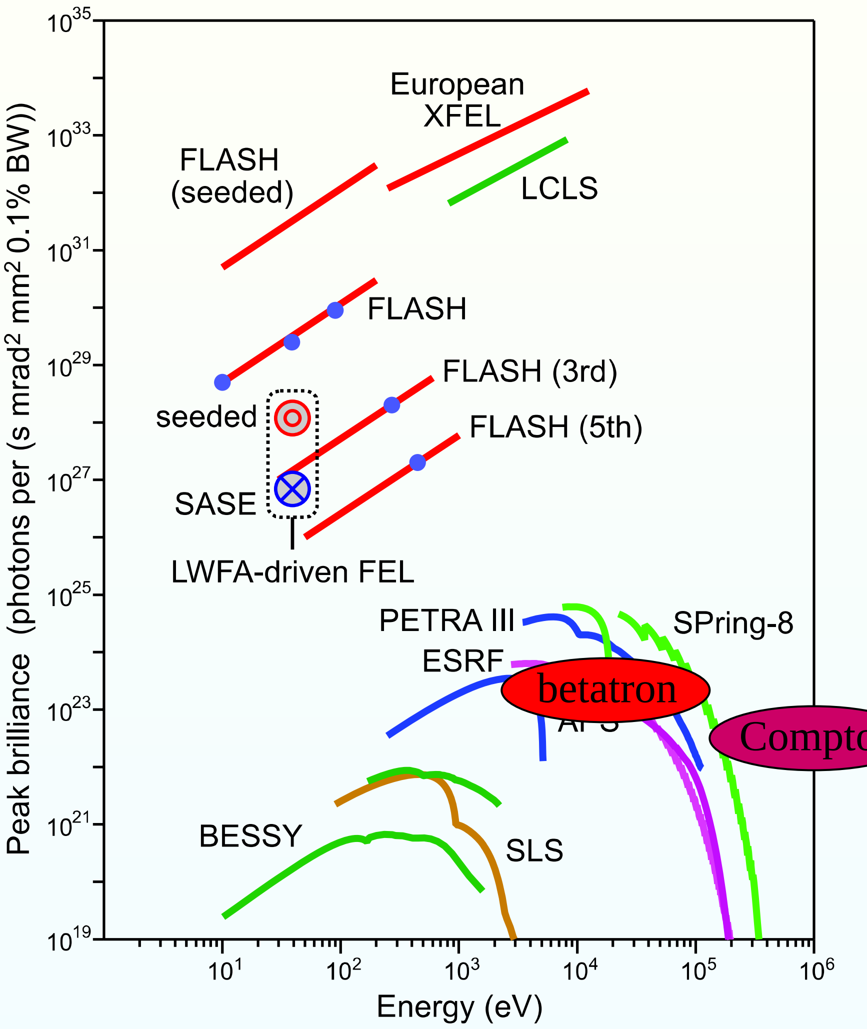
- One long-term goal is development of compact free-electron lasers driven by plasma accelerators

- Spontaneous radiation causes electron microbunching on scale of radiation wavelength
- Leads to coherent emission of radiation; self-amplification
- Exponential gain in power output

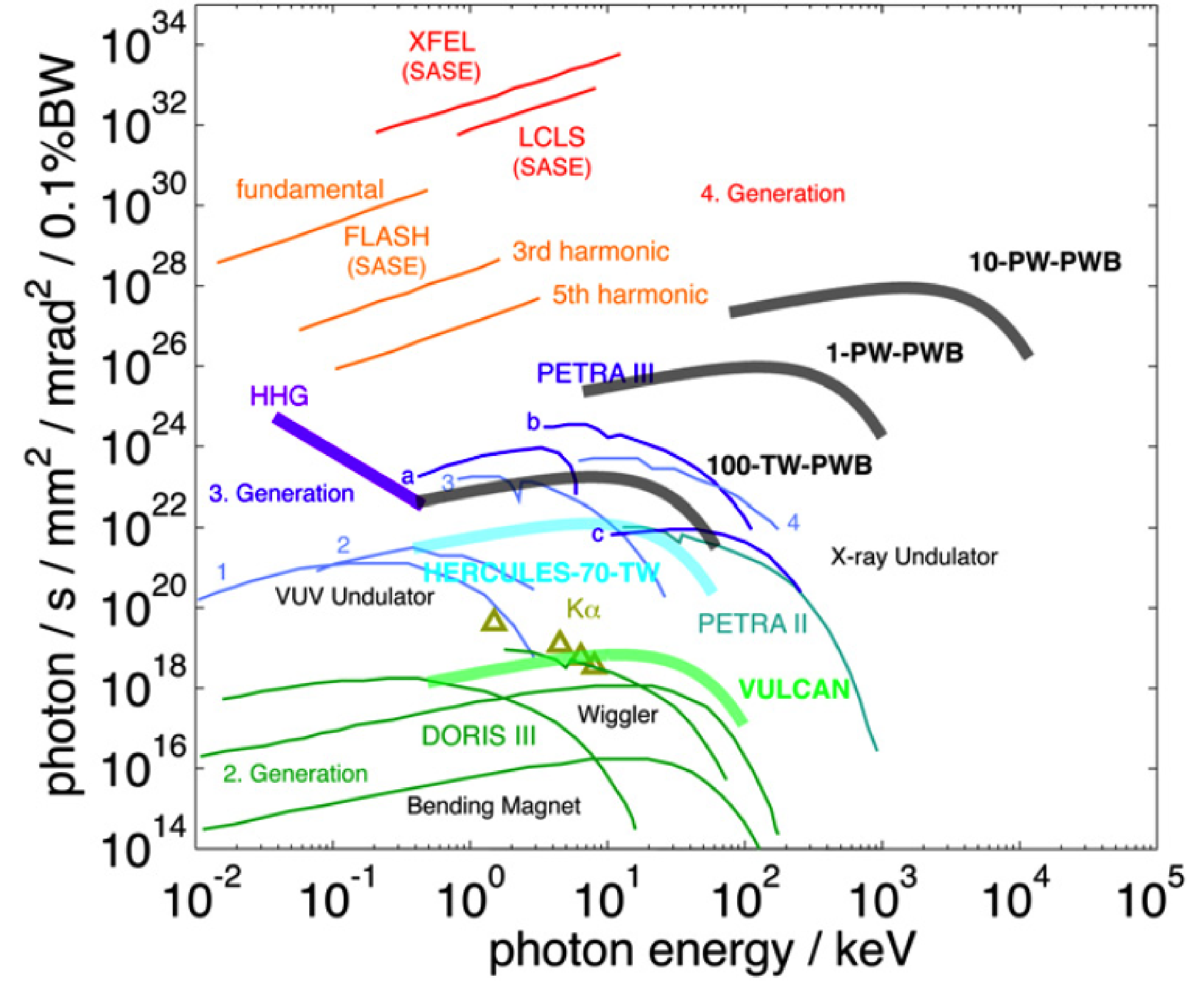
Challenges & future work

Compact light sources driven by plasma accelerators have enormous potential, but many challenges remain:

- **Better characterisation of e-beam parameters**
  - ⇒ Novel diagnostics
- **Improve shot-to-shot stability of e-beam parameters**
  - ⇒ Control injection process
- **Understand beam transport issues**
  - ⇒ Novel beam optics, modelling
- **Increase repetition rate**
  - ⇒ Develop novel laser drivers
- **To decrease wavelength, increase beam energy**
  - ⇒ Staging plasma accelerators, tapered plasmas
- **Develop applications**
  - ⇒ Characterise sources, undertake “proof-of-principle” experiments



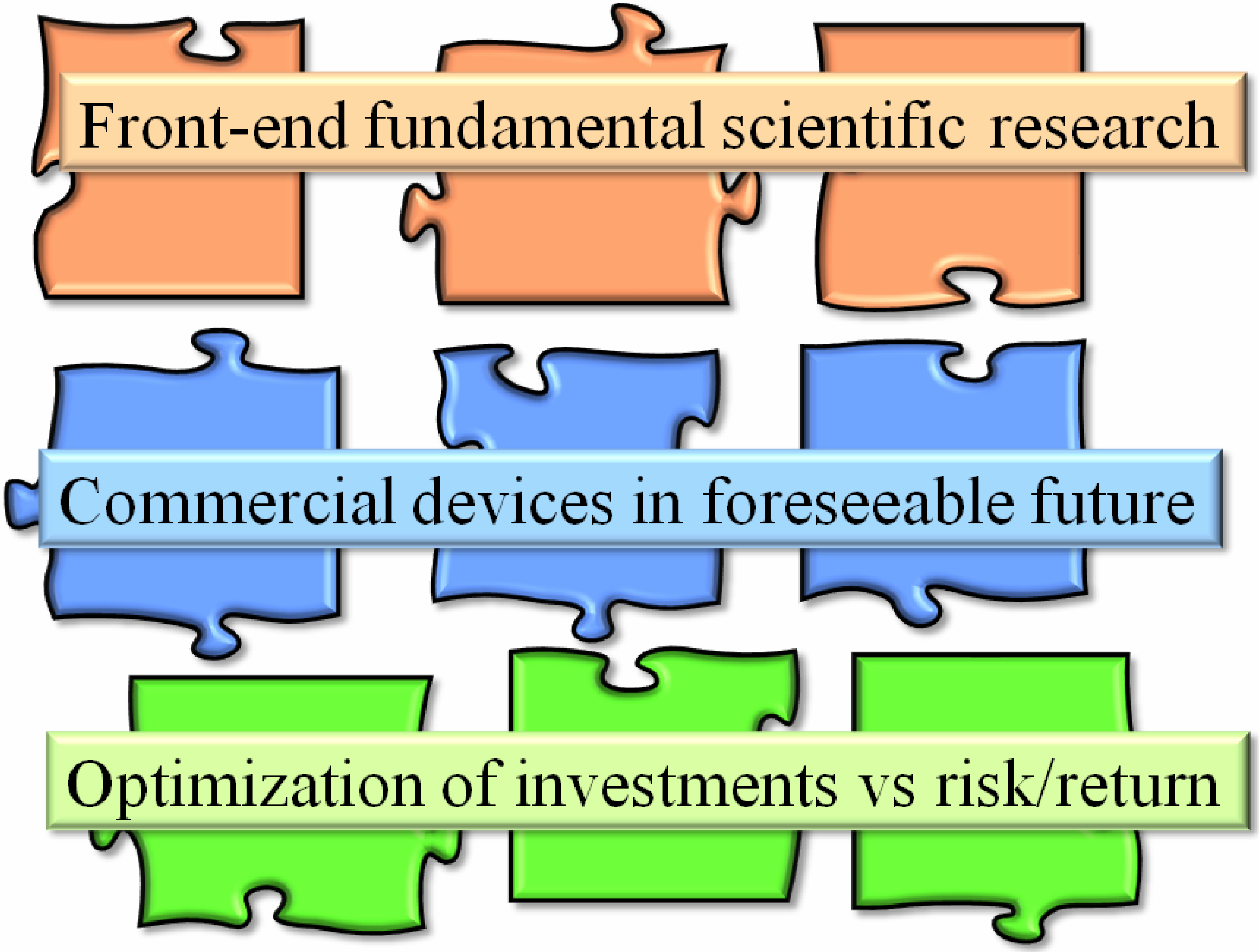
Conventional and Laser-Plasma sources



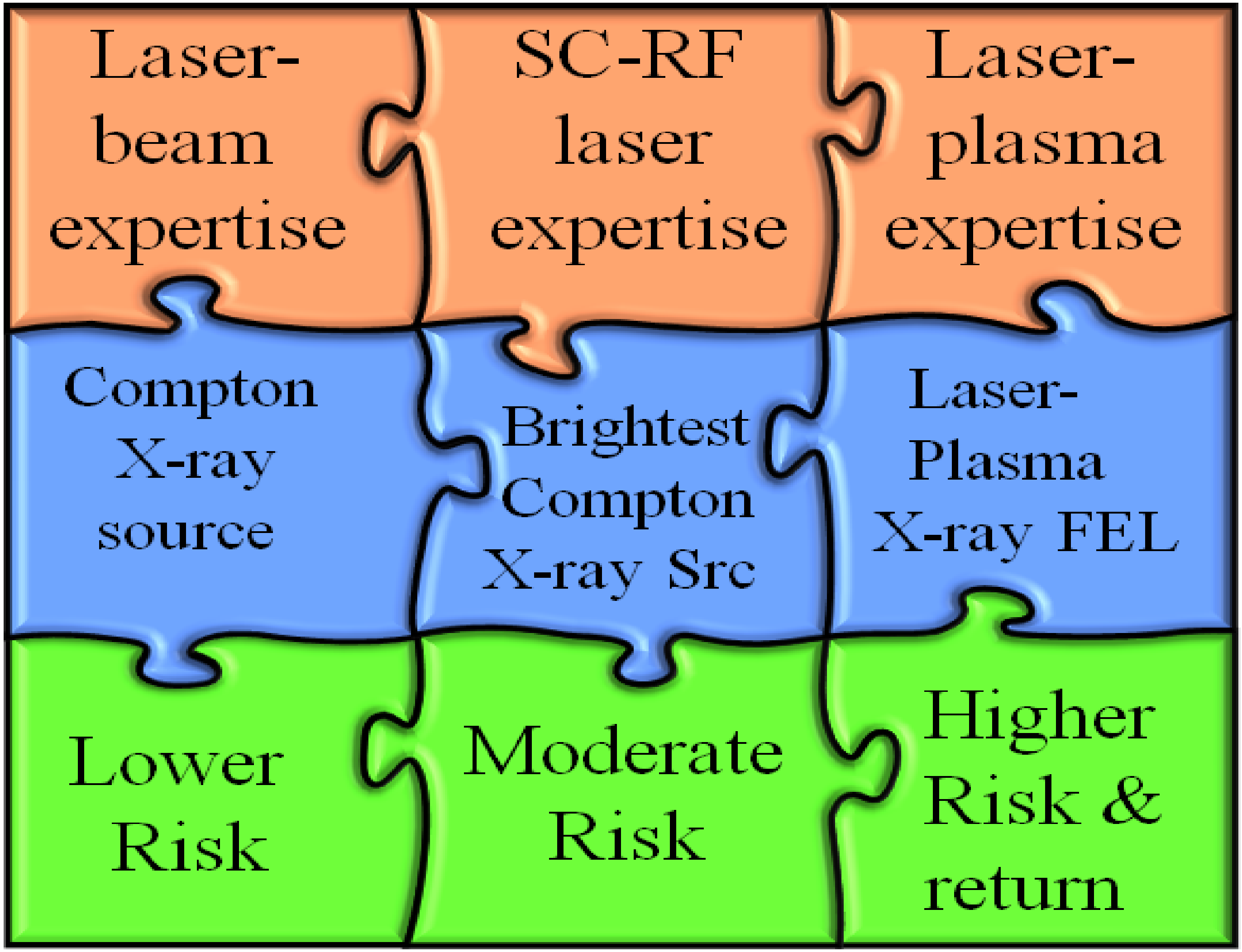
From: "A plasma wiggler beamline for 100 TW to 10 PW lasers", Stefan Kneip, Zulfikar Najmudin, Alexander Thomas, High Energy Density Physics 8 (2012), p.133-140.


Imperial College London
Royal Holloway University of London
UNIVERSITY OF OXFORD
JAI
John Adams Institute for Accelerator Science
PHYSICAL REVIEW LETTERS
PHYSICAL REVIEW LETTERS
Patent
Patent
Niels Bohr
Louis Pasteur
Thomas Edison
Accelerator Science and Technologies
Protons/Ions
Fundamental knowledge
Consideration of use

Academia-Industry-Investor puzzle



Academia-Industry-Investor puzzle solved



Crossing the "Valley of Death"

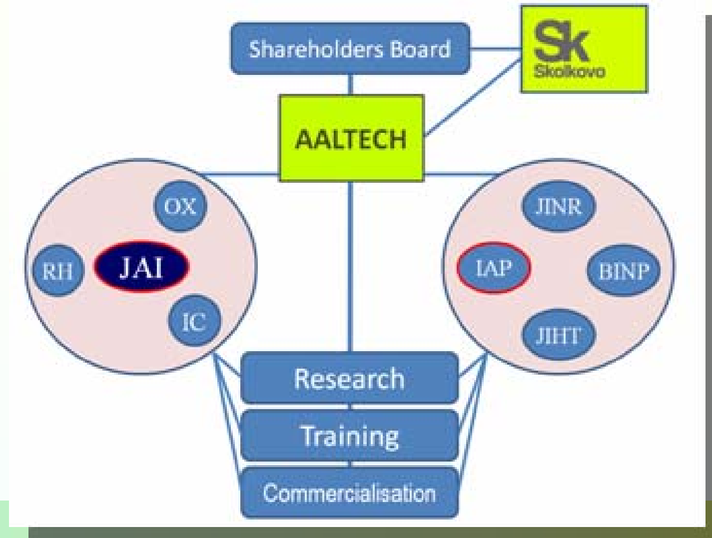
Working on a portfolio of compact X-ray light sources will help crossing the "Valley of Death" between accelerator science and technological innovation

PS Public Service Review, UK Science and Technology, issue 04 www.publicservice.co.uk

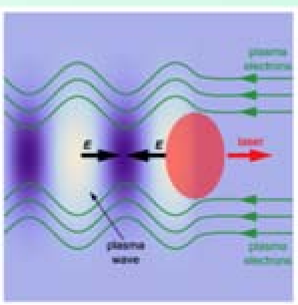
Applied Research Centre in laser-plasma acceleration

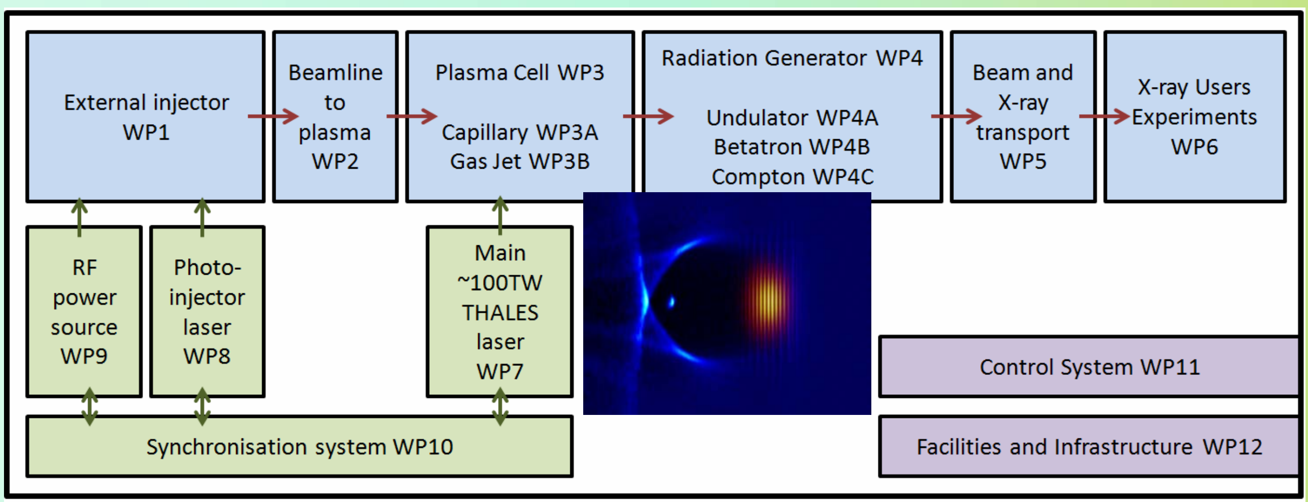
John Adams Institute J.A.I. for Accelerator Science | Imperial College London | Royal Holloway University of London | University of Oxford | ИПФ РАН | Skolkovo

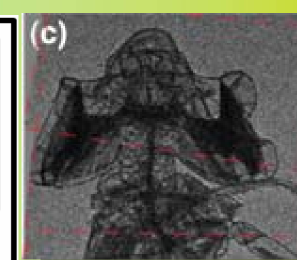
- **Aim: compact laser-plasma-based X-ray FEL**
- **Partners:**
  - **JAI, Oxford, RHUL, Imperial College (UK)**
  - **IAP, BINP, JIHT, JINR, AALTECH, Sk Nuclear Cluster (RU)**
- **Based on:**
  - **Pioneering results of Oxford and Imperial College**
  - **Ultra-high gradient laser-plasma acceleration**
  - **Flexible design, internal or external injection**
  - **State of the art 170TW laser, upgradable to PW level**



compact laser-plasma X-ray source & FEL







S. Kneip et al., Appl. Phys. Lett. 99, 093701 (2011)

Summary

- An new direction is emerging in accelerator science – compact x-ray sources, enabled by the synergy of accelerators and lasers, where high gradient laser-plasma acceleration can significantly reduce the size and cost of the facilities
- Compact x-ray sources will be developed in the nearest future and will share their scientific and market niche with large national scale x-ray facilities
- The compact sources will in particular be suitable for placement in universities and medical or technological centres
- Development of compact x-ray FEL is a promising topic for scientific and technological collaboration between UK and Russia, where expertise of partners will cross-fertilize their ability to solve scientific and technological challenges