Optimisation of compact laser-driven accelerator x-ray sources for industrial imaging applications

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http://www.clf.stfc.ac.uk/

Science & Technology Facilities Council

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Advanced detectors

Industrial engagement

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10 Years of Impact and Inspiration

CATAPULT
High Value Manufacturing

mtc
Manufacturing Technology Centre

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WMG
THE UNIVERSITY OF WARWICK

Henry Moseley
X-Ray Imaging Facility

UNIVERSITY OF Southampton
μ-VIS | www.muvis.org

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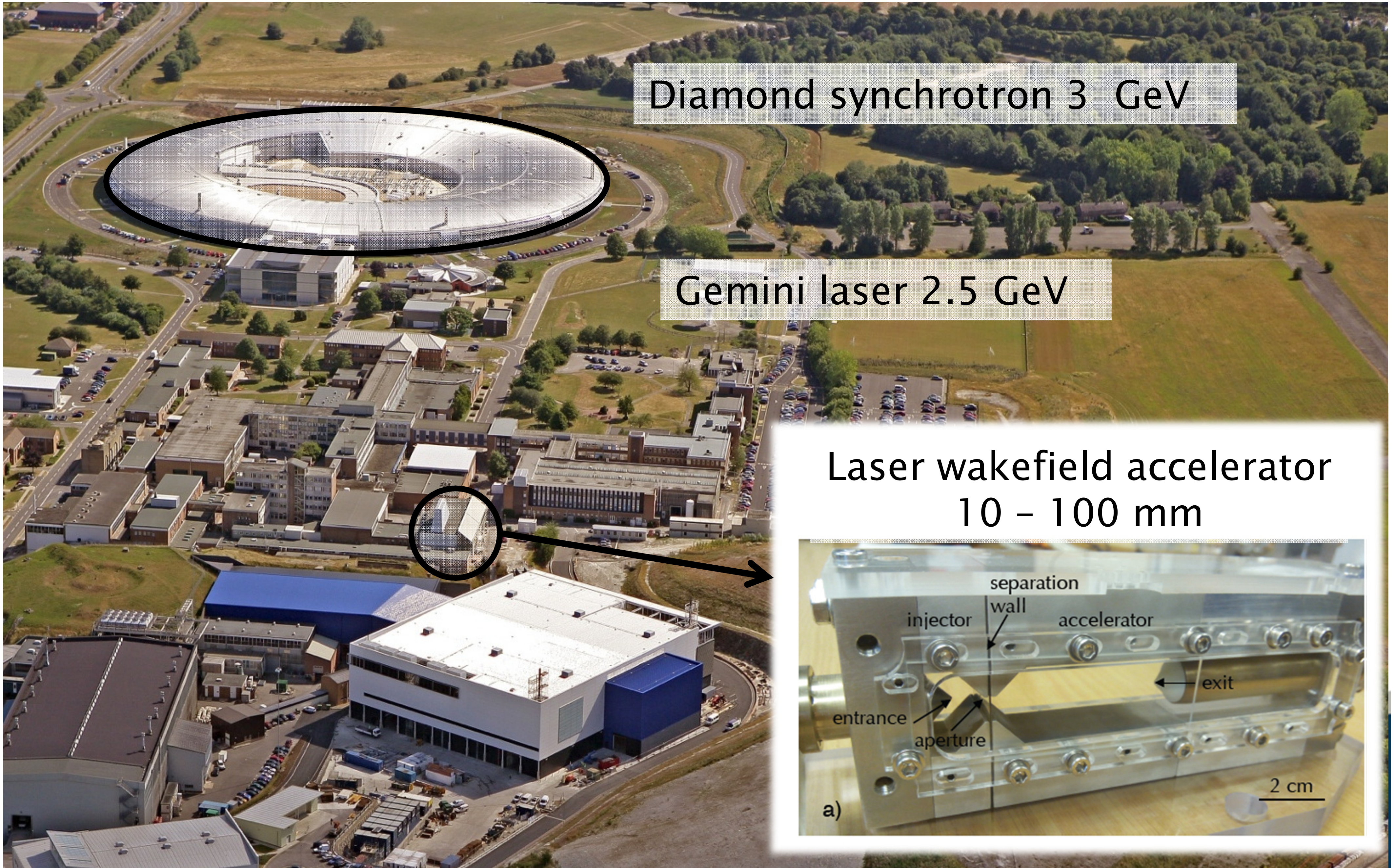
Key properties for industrial x-ray beams

1. **Penetration**
   - ➢ Hard x-rays 10 – 1000 keV
2. **Resolution**
   - ➢ Operating at the limits of x-ray source size & detector
3. **Acquisition speed**
   - ➢ Acceptable time for 4-D scanning
4. **Phase contrast**
   - ➢ Enhances visibility between materials of similar density

Compact bright laser x-ray sources bring synchrotron capability to the lab



Many laser systems are now running with *Petawatt-class* parameters

2007 UK Gemini laser facility

- Ti:Sapphire → 30 fs
- ~10 J for 0.2 – 0.3 PW, 1 pulse / 20 sec
- Few systems, built by national facilities

2018 Many lasers worldwide

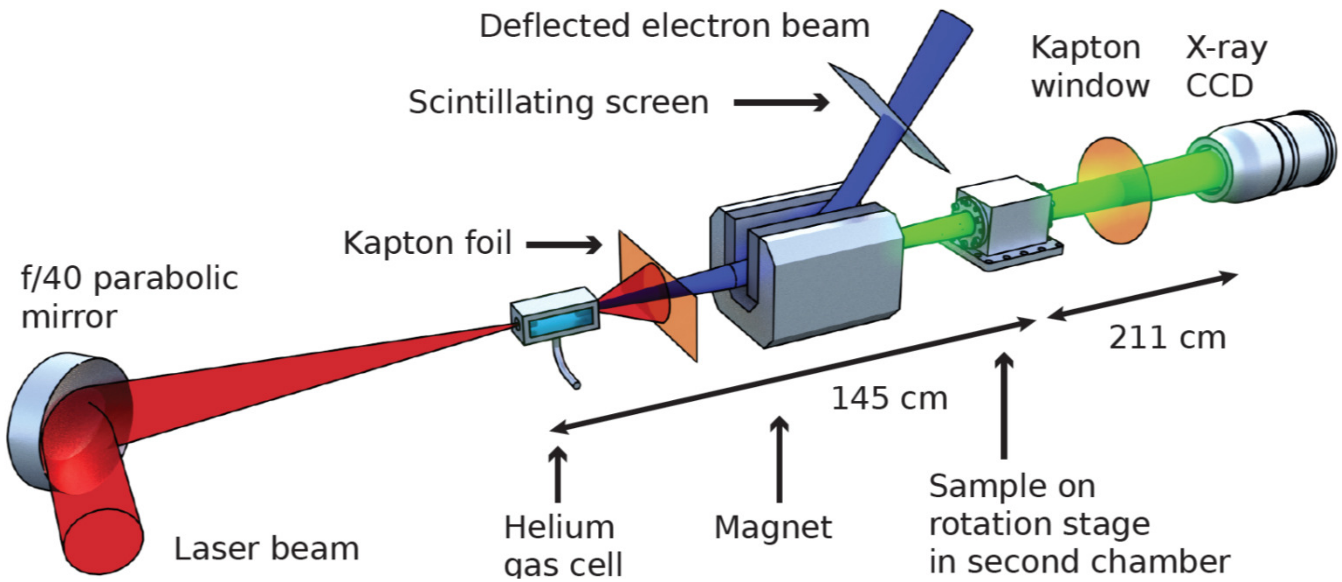
- 10 – 50J, 0.1 – 1 PW
- 1- 10 Hz repetition rate
- Commercialised → reliable, robust, compact

Future developments

- 10 Hz PW secondary source facilities, e.g. ELI-Beamlines
- PW at 100 Hz – multi kHz rep-rates
- 10 – 100 PW power lasers

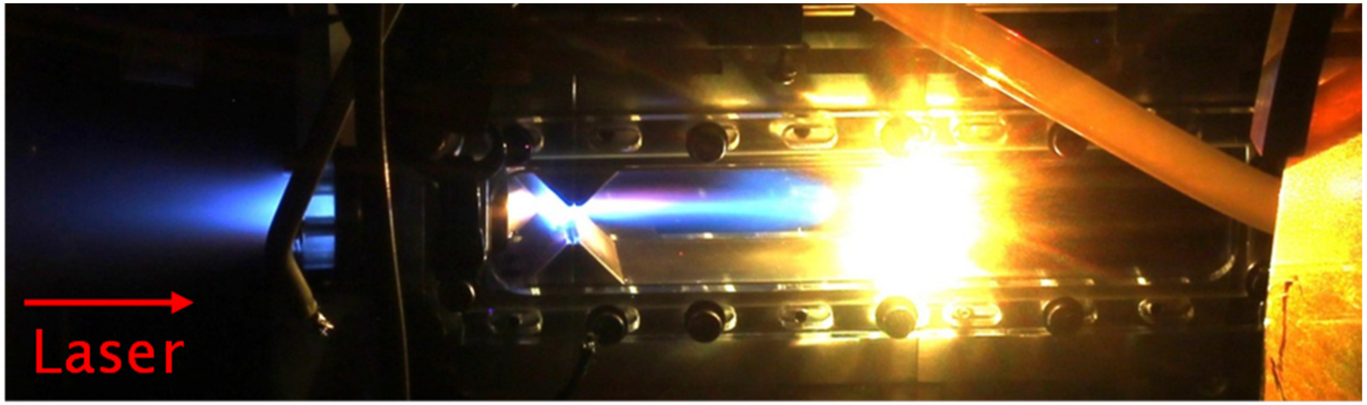
Danson, "**Petawatt class lasers worldwide**"
High Power Laser Science and Engineering, 3.
doi:10.1017/hpl.2014.52

Compact laser-driven electron accelerator



Gemini 14J, 40fs, 350TW

- Loose focus parabola for 20μm spot
- Propagates through few cm gas target
- Intensity ~10^{19} Wcm^{-2}



Field strength up to 100 GV/m behind the laser pulse

Kneip, "**A plasma wiggler beamline for 100 TW to 10 PW lasers**" *High Energy Density Physics,* 8, 133 (2012)

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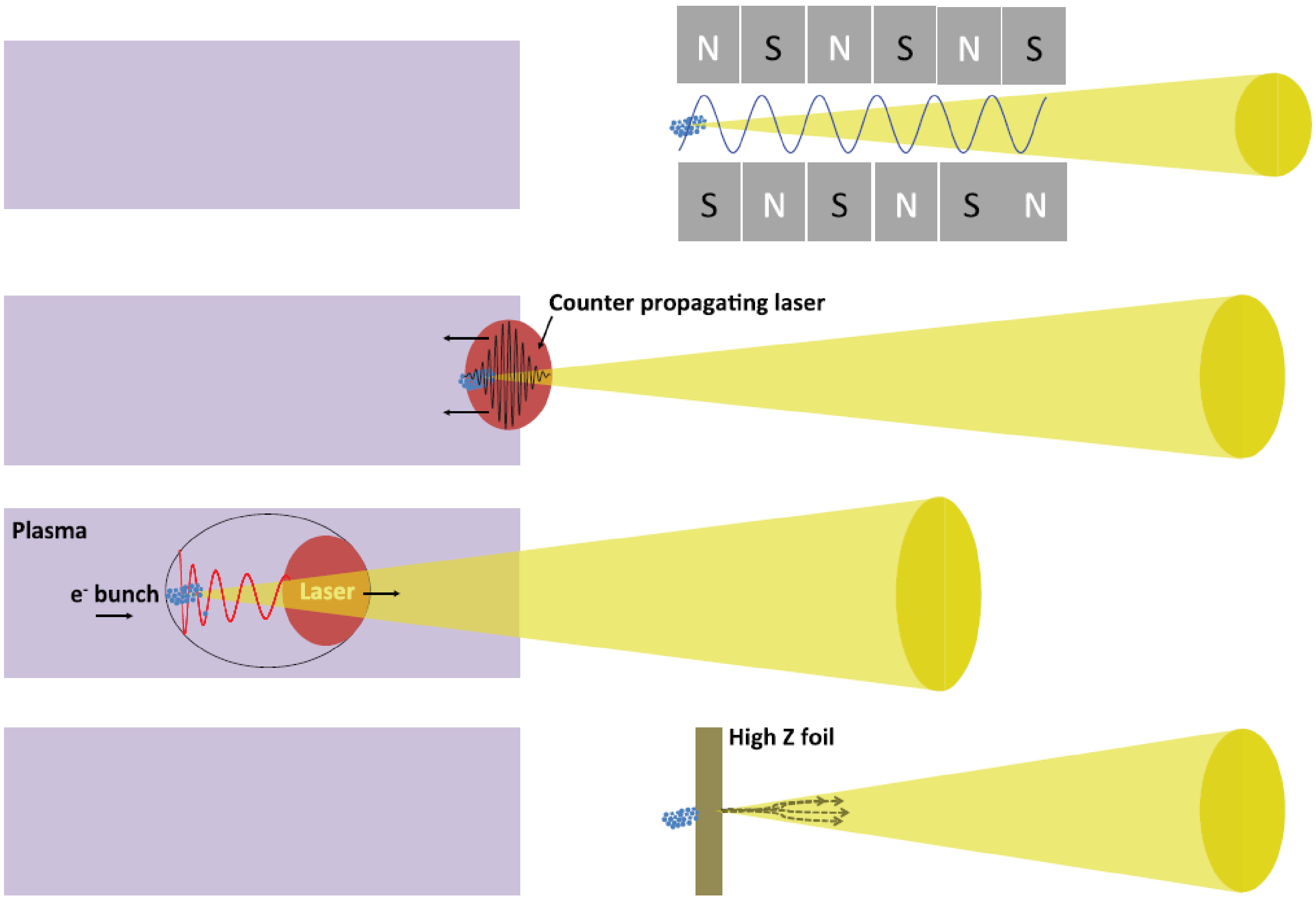
Relativistic electron beams can be converted to bright x-ray sources



Undulator / XFEL
UV – few keV

Inverse Compton Scattering
> MeV

Betatron
Few keV - MeV

Bremsstrahlung
> MeV

Albert, "Applications of laser wakefield accelerator–based light sources" *Plasma Phys. Control. Fusion 58, 103001 (2016)*

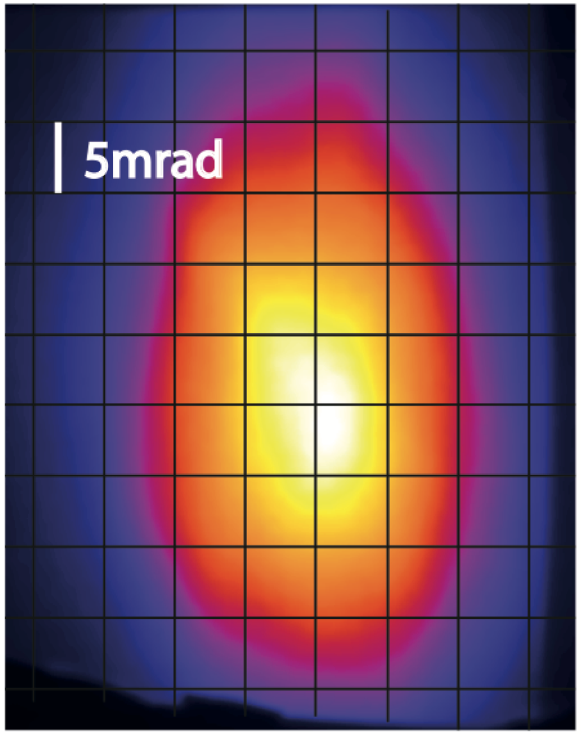
Gemini produces stable beams with high energy (2 GeV) and high charge (~0.5nC)

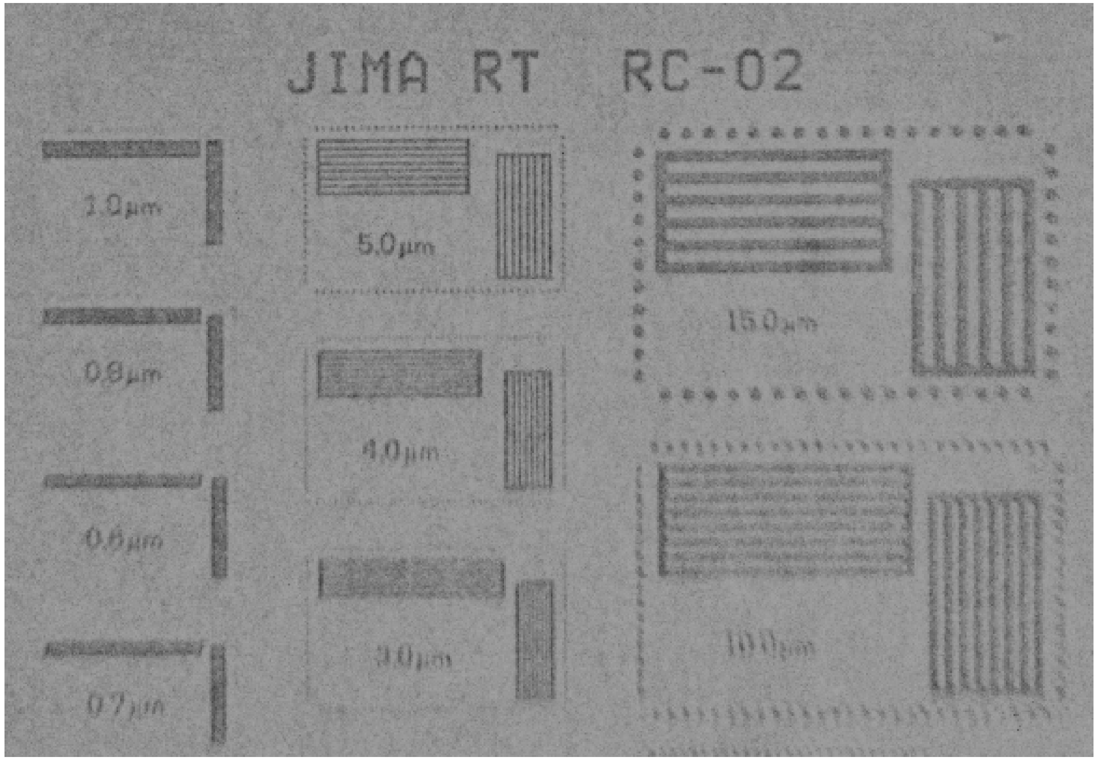
Redacted image shows electrons energies and betatron x-ray beams measured as the gas cell length is increased from 3 mm to 40 mm.

Injection of second bunch – lower energy (<800 MeV) but high charge

Good regime for betatron and bremsstrahlung conversion

High brightness 23 keV laser-betatron source with micron source size





- $>10^9$ photons per 5J laser pulse
- Synchrotron energy distribution
- Critical energy E_{crit} = 23 keV
- 10 mrad FWHM divergence
- Inferred source size < 1 μm

JIMA resolution grid imaged with laser-betatron at *M* = 10 (detector limited resolution)

John Adams Institute for Accelerator Science

Imperial College London

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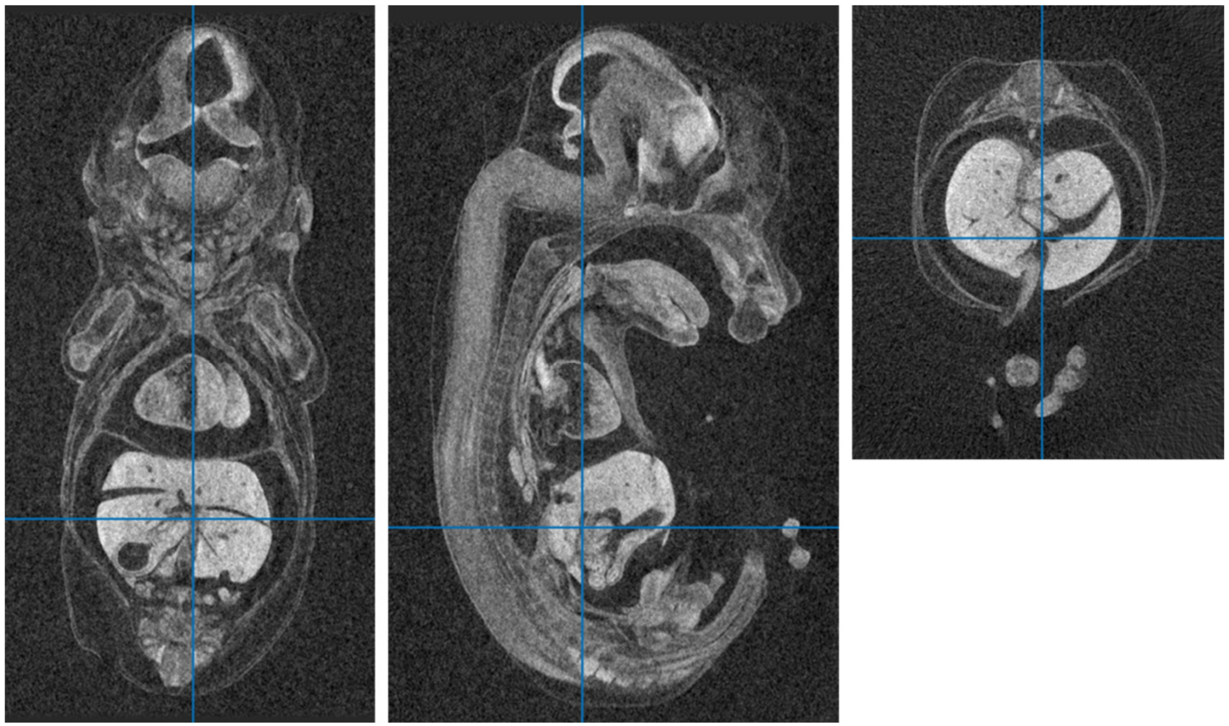
High resolution μCT shown with biological samples



Single shot acquisition allows in vivo imaging and rapid data collection for phenotyping

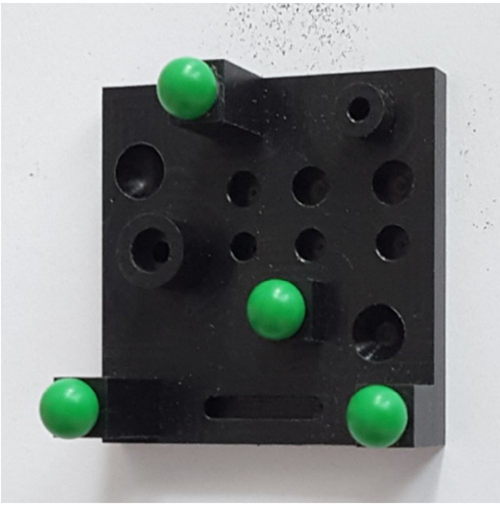
Cole, "High resolution μCT of a mouse embryo using a compact laser-driven x-ray betatron source"
PNAS 10.1073/pnas.1802314115 (2018)

High resolution metrology required to define manufacturing standards

Dimensional XCT

- Metrology of plastic and aluminium test objects from WMG
- Should be able to reach sub-μm resolution with improved detectors

Single shot betatron imaging of low *Z* samples



Redacted images show x-rays of these samples obtained using the betatron source

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New battery technologies need advanced inspection methods

THE FARADAY INSTITUTION
Energy Storage Research

Faraday Challenge

- Large UK investment (£246M)
- New electrode materials
- Better understanding of degradation

Redacted image shows x-ray of this sample obtained using the betatron source

Laser-betatron imaging of battery

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Huge demand for composite materials needs increase in production efficiency

In-process characterisation

- Define defect tolerances
- Reduce scrap rate

Redacted images show x-rays of composite samples obtained using the betatron source

- Better resolution (~μm) and faster scans
- Distinguish low *Z* materials through phase enhancement

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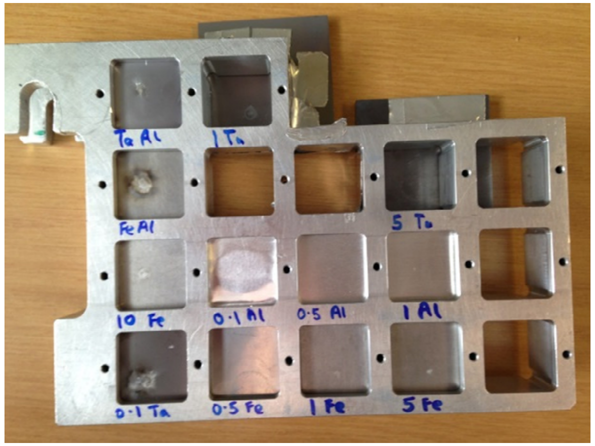
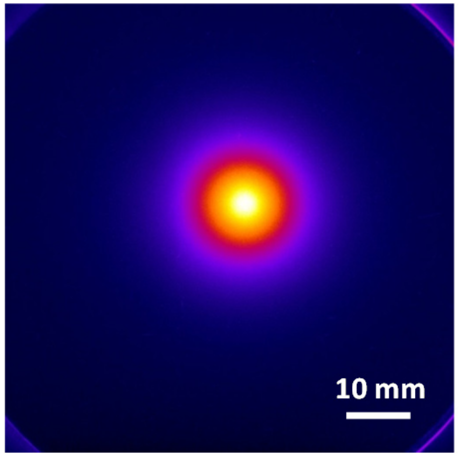
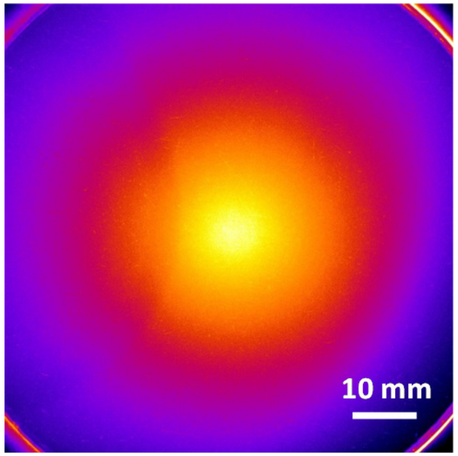
Bremsstrahlung divergence and energy controlled by choice of convertor



Range of convertors 100µm Al to 5000µm Ta

Redacted image shows x-ray of resolution target obtained using the bremsstrahlung source

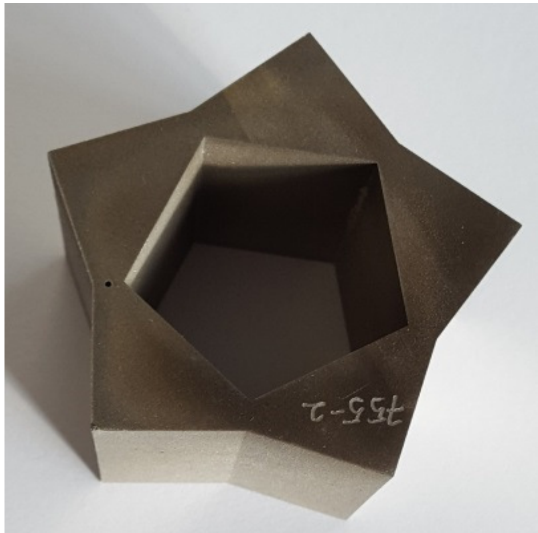




- 5 mm thick Ta resolution target
- Compare with industrial LINAC ~ mm resolution

X-ray beam detected on LYSO
100's MeV e- → multi-MeV x-rays

Bremsstrahlung imaging of high density nickel AM test object



Redacted images show x-rays of this sample obtained using the bremsstrahlung source

Nickel AM test object

- Preliminary angle scan
- ~50% transmission
- Resolution limited by hard x-ray detectors

Bremsstrahlung imaging of titanium alloy fanblade

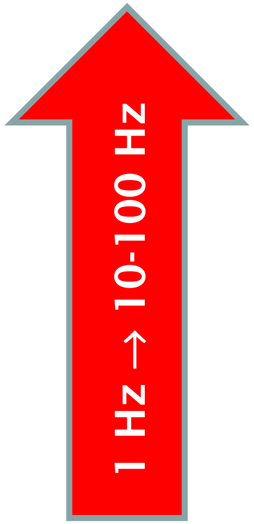
Redacted image shows x-ray of this sample obtained using the bremsstrahlung source

Ti-alloy fanblade

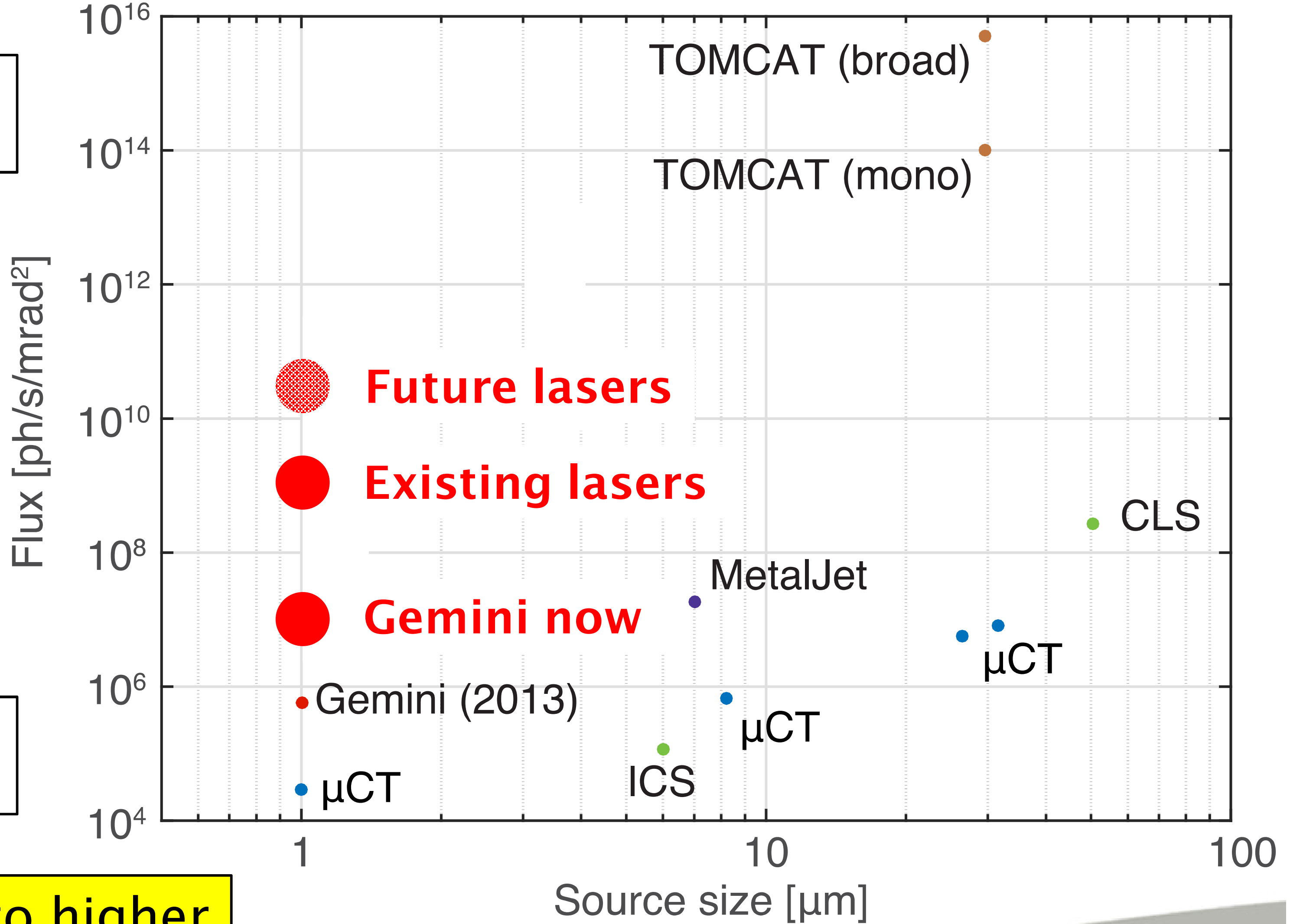
- Internal honeycomb structure
- ~250 μm wall thickness resolved
- Structure seen with good contrast

Image acquisition is currently limited by laser repetition rate

- *Diode pumping*
- *>10 Hz PW lasers*



- *Gemini 1 shot/ 20 sec*
- *Bella (LBNL) 1 Hz*



Betatron can scale to higher photon flux without an increase in source size

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Conclusion

High power lasers generate extreme brightness x-rays

- Synchrotron-style performance with a lab-based source
- Increase to 10 Hz possible with existing lasers

Attractive properties for industrial imaging

- High penetration at high resolution
- High frame rate for in-process quality control

Proof of principle demonstrations

- Metrology test objects
- Battery materials
- Composites