Industry Connections

Laurie Nevay, RHUL

on behalf of the JAI

JAI Advisory Board - 19th April 2021

Introduction

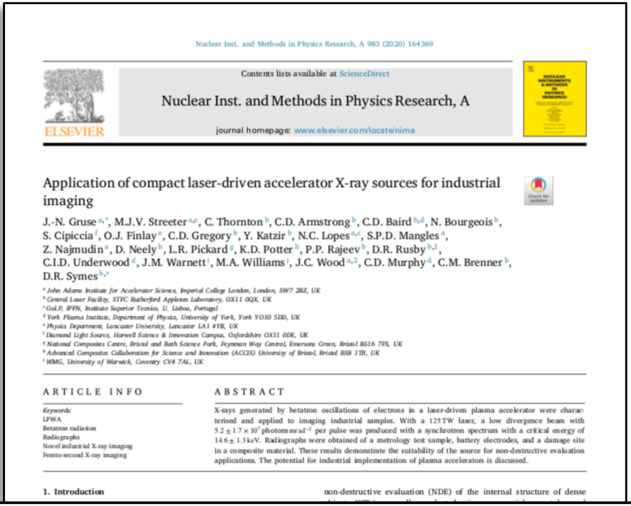
- The JAI has fundamental science at its heart, but an increasing part of its mission is promoting advanced accelerator applications in science and society
- Connection with industry is a natural and valued part of its activity
- Overview of recent industry connections presented here:
  - betatron imaging
  - CLIC RF
  - industrialisation of BPMs for FELs
  - precision metrology
  - medical beam line system simulation
  - radiation transport simulation
  - additional Oxford commercialisation activity

> - JAI industrial activity is supported by technology transfer experts that reside in each institution
> - They guide or manage aspects of IP/contracts/fundraising etc to enable the pathway to commercialisation and support JAI researchers to make strategic decisions on commercialisation of the technology

Betatron Imaging

Z. Najmudin

- Use betatron radiation from plasma-based electron accelerator
- Compact X-ray source comparable to national-level facilities
- Wide variety of applications in (recent) industry
  - non-destructive evaluation (NDE) of internal structure
  - complex forms now made with additive manufacturing
  - novel battery technology and structures
  - evaluation of composite materials



Nuclear Inst. and Methods in Physics Research, A 983 (2020) 164369

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Application of compact laser-driven accelerator X-ray sources for industrial imaging

J.-N. Gruse[a,*], M.J.V. Streeter[a,e], C. Thornton[b], C.D. Armstrong[b], C.D. Baird[b,d], N. Bourgeois[b], S. Cipiccia[f], O.J. Finlay[e], C.D. Gregory[b], Y. Katzir[b], N.C. Lopes[a,c], S.P.D. Mangles[a], Z. Najmudin[a], D. Neely[b], L.R. Pickard[g], K.D. Potter[h], P.P. Rajeev[b], D.R. Rusby[b,1], C.I.D. Underwood[d], J.M. Warnett[i], M.A. Williams[i], J.C. Wood[a,2], C.D. Murphy[d], C.M. Brenner[b], D.R. Symes[b,*]

[a] John Adams Institute for Accelerator Science, Imperial College London, London, SW7 2BZ, UK
[b] Central Laser Facility, STFC Rutherford Appleton Laboratory, OX11 0QX, UK
[c] GoLP, IPFN, Instituto Superior Tecnico, U. Lisboa, Portugal
[d] York Plasma Institute, Department of Physics, University of York, York YO10 5DD, UK
[e] Physics Department, Lancaster University, Lancaster LA1 4YB, UK
[f] Diamond Light Source, Harwell Science & Innovation Campus, Oxfordshire OX11 0DE, UK
[g] National Composites Centre, Bristol and Bath Science Park, Feynman Way Central, Emersons Green, Bristol BS16 7FS, UK
[h] Advanced Composites Collaboration for Science and Innovation (ACCIS) University of Bristol, Bristol BS8 1TR, UK
[i] WMG, University of Warwick, Coventry CV4 7AL, UK

ARTICLE INFO

Keywords:
LPWA
Betatron radiation
Radiographs
Novel industrial X-ray imaging
Femto-second X-ray imaging

ABSTRACT

X-rays generated by betatron oscillations of electrons in a laser-driven plasma accelerator were characterised and applied to imaging industrial samples. With a 125 TW laser, a low divergence beam with $5.2 \pm 1.7 \times 10^7$ photons mrad^{-2} per pulse was produced with a synchrotron spectrum with a critical energy of 14.6 ± 1.3 keV. Radiographs were obtained of a metrology test sample, battery electrodes, and a damage site in a composite material. These results demonstrate the suitability of the source for non-destructive evaluation applications. The potential for industrial implementation of plasma accelerators is discussed.

1. Introduction

non-destructive evaluation (NDE) of the internal structure of dense

https://doi.org/10.1016/j.nima.2020.164369

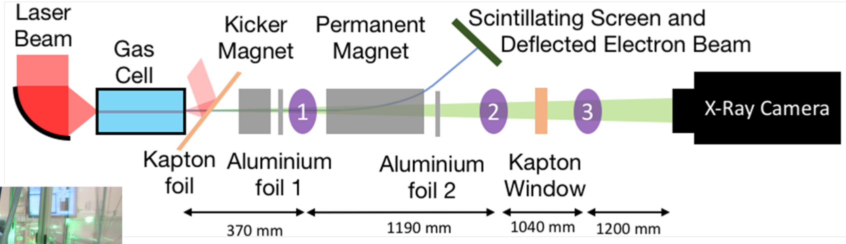
Imperial College London

Betatron Imaging Experiments

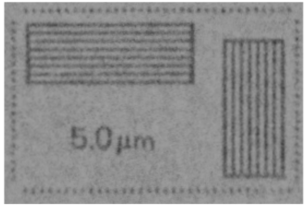
Z. Najmudin

- A number of experiments have been carried out with collaborators at RAL
- View to testing for industrial applications
  - using Gemini laser
  - 15 J at 800 nm in 2 independent beams
  - pulse length < 40 fs, at 20s repetition rate
  - f/40 for LWFA (a0 ~ 4)

typical imaging setup

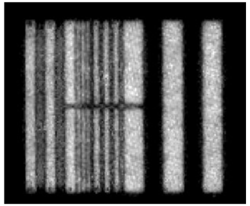


synchrotron spectrum with
E_{crit} = 17.2 ± 1.6 keV
r_β =1.2 ± 0.2μm
7.4 ± 2.6 × 10^8 photons $mrad^{-2}$
in θ ~10 mrad



resolution target imaged at position 1 (M=10.2)

c)



gold grid imaged at position 2 (M=2.2)

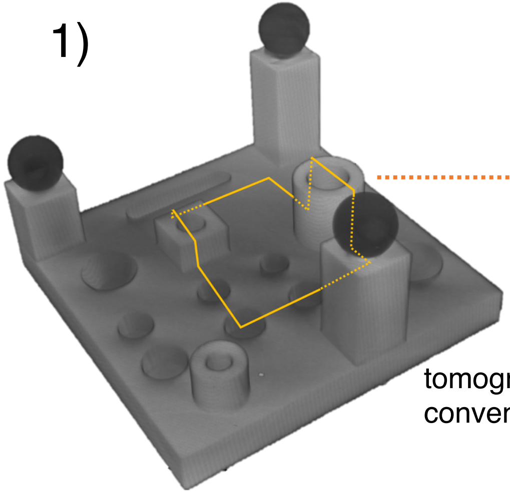
John Adams Institute for Accelerator Science

Betatron Imaging Results

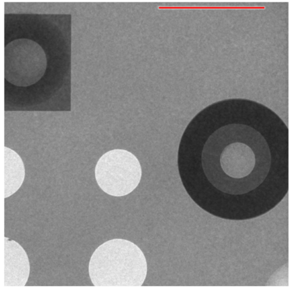
Z. Najmudin

plastic 3D-printed test for XCT performance verification

1)

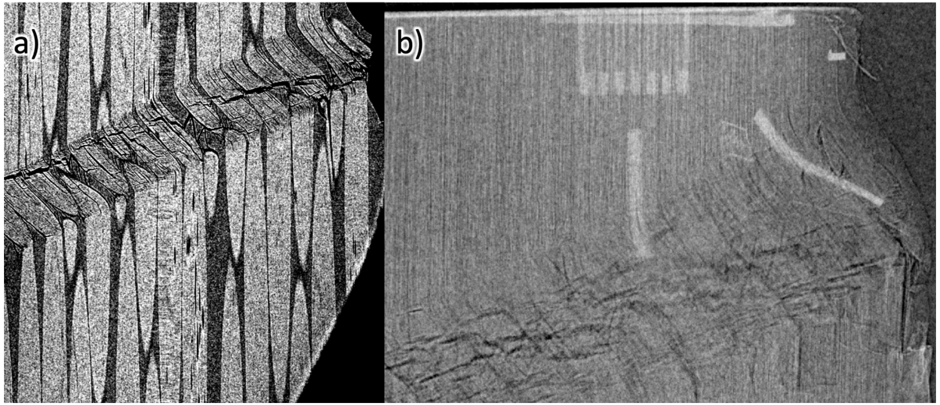


radiograph with the laser-betatron source



tomographic reconstruction using conventional lab x-ray CT

2) Betatron imaging used for phase contrast imaging of carbon fibre with kink band failure

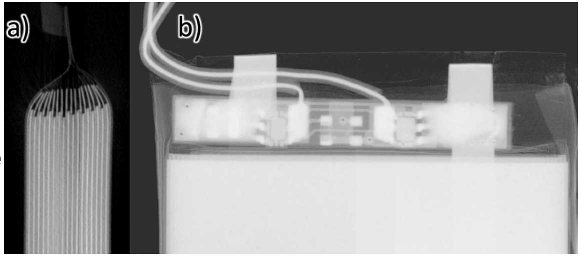


conventional X-ray source

betatron X-ray source

3)

radiograph obtained with the laser-betatron source with carbon fibre tows visible



novel lithium battery configurations

Extreme Photonics Application Centre

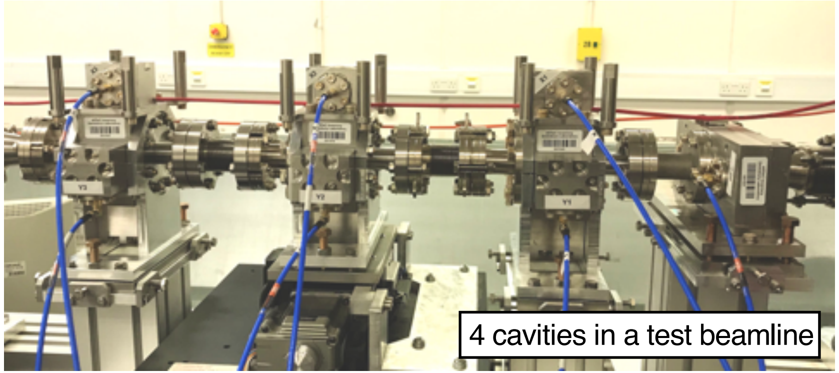
Z. Najmudin

- > £81m facility being constructed at Rutherford-Appleton Laboratory
- One of the major uses for EPAC will be betatron imaging and other X-ray techniques synchronised to secondary light and particle sources.

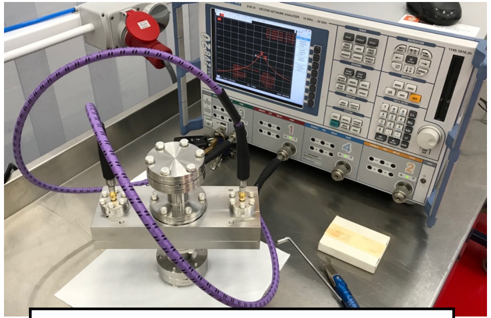
Industrialisation of BPMs for FELs

A. Lyapin

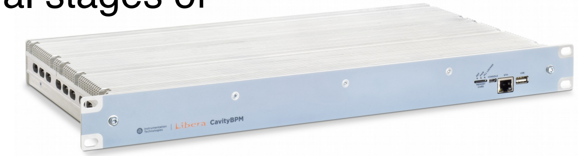
- Cavity BPM designed for FELs
  - underpinning research: precision diagnostics for linear colliders
- Formal partnerships with FMB-Oxford and Instrumentation Technologies
  - supported by STFC IPS grant 2013-2017
- Complete off-the-shelf system
- Cavity design licensed to FMB-Oxford in 2019
- First contracts granted to both FMB and iTech in 2020 by ELI-BL, total ~€250k
- Electronics delivered, cavities in the final stages of testing and tuning
- REF2021 case study submitted



4 cavities in a test beamline



ELI BL cavities on the test bench

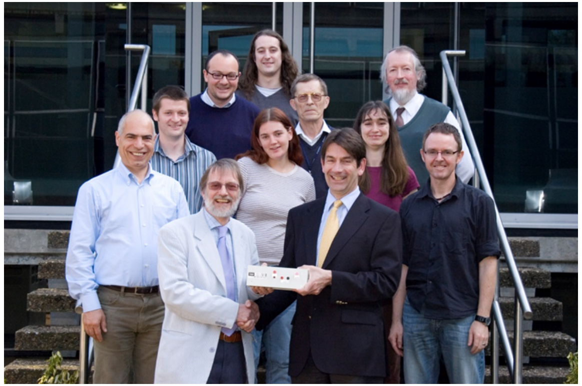


iTech's Libera Cavity BPM now works with FMB's cavities

Oxford RF Work

P. Burrows

- Burrows has a long-standing collaboration with UK advanced RF manufacturer TMD Technologies Ltd. (Hayes)
- Jointly developed low-latency, high-power RF amplifier for beam feedback systems for ILC, deployed at KEK/ATF2
- TMD sponsored PhD students via STFC 'CASE' scheme:
  - ***Rebecca Ramjiawan* (2019)**
    - Development of feedback algorithms for future linear colliders
  - ***Neven Blaskovic Kraljevic* (2015)**
    - Development of a high-precision low-latency position feedback system for single pass beamlines using stripline and cavity BPMs
  - ***Christine Clarke* (2008)**
    - The interaction point collision feedback system at the ILC and its sensitivity to expected electromagnetic backgrounds
- CERN supported Doctoral Student on CLIC X-band structure performance:
  - ***Jan Paszkiewicz* (2020)**
    - Studies of breakdown and pre-breakdown phenomena in high gradient accelerating structures
- This connection, and Burrows' Spokespersonship of CLIC, led to TMD being qualified for bonding / brazing of CLIC X-band structures, with first structure assembled (2019/20)

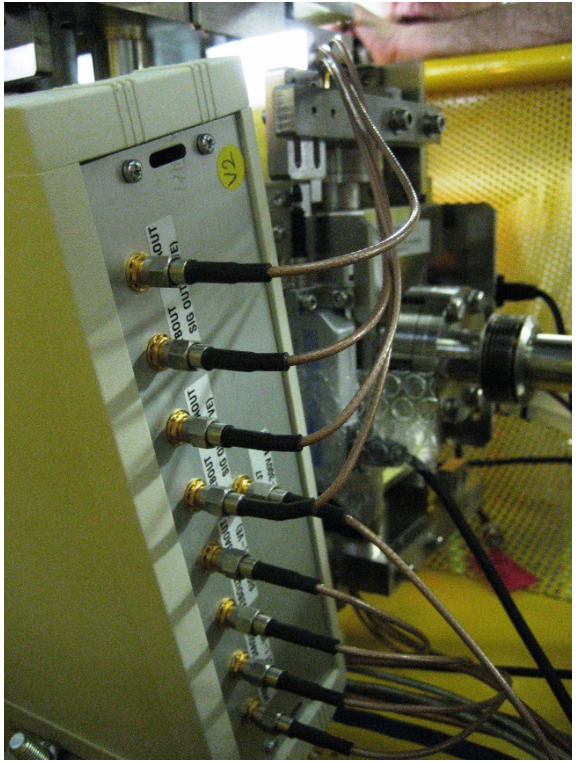


John Adams Institute for Accelerator Science

FONT Drive Amplifier

P. Burrows

- Outline design done in JAI/Oxford
- Production design + fabrication by TMD Technologies
- Specifications:
  - ± 15A (kicker terminated with 50 Ohm)
  - ± 30A (kicker shorted at far end)
  - 35ns risetime (to 90%)
  - pulse length 10 us
  - repetition rate 10 Hz



UNIVERSITY OF OXFORD

CLIC Industrialisation

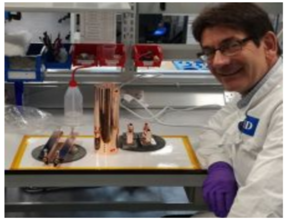
Department of Physics

News | Nurturing links with industry for results in scientific research

News
- Admissions
- Alumni
- Enterprise
- IT
- Newsletters
- Research
- Featured
- Outreach

Nurturing links with industry for results in scientific research

3 February 2021



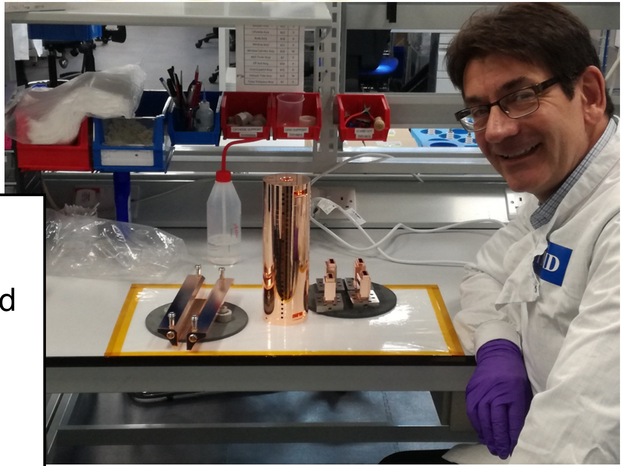
Professor Philip Burrows has been working with UK company TMD Technologies to design key elements of a next-generation electron-positron collider at CERN. Professor Burrows leads the Compact Linear Collider (CLIC) Collaboration which is preparing the design of the collider that could serve as a 'factory' for mass-producing Higgs bosons. Such a Higgs factory has been identified by the global particle physics community as its top priority for a next-generation subatomic particle collider facility.

Pushing the boundaries of technology

THE MAGAZINE FOR THE CUSTOMERS OF TMD

MARCH 2021 | ISSUE NO. 36

TMD IN FOCUS



- Steady stream of CLIC prototypes
- CLIC would eventually need tens of thousands

Developing applications:
- compact light sources
- VHEE therapy
- FLASH therapy
  (see also Manjit's talk)

P. Burrows

John Adams Institute for Accelerator Science

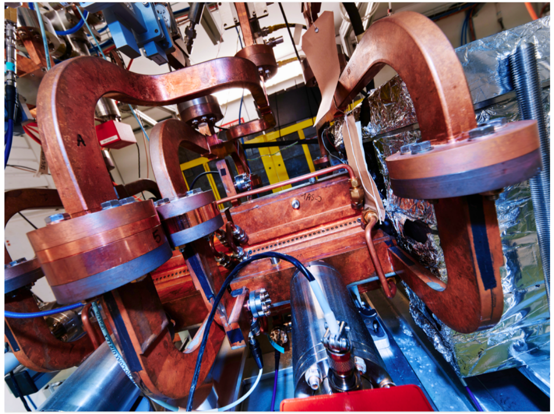
P. Burrows, M. Dosanjh

CLIC for Medical Applications

CERN and Lausanne University Hospital collaborate on a pioneering new cancer radiotherapy facility

CERN and the Lausanne University Hospital (CHUV) are collaborating to develop the conceptual design of an innovative radiotherapy facility, used for cancer treatment

15 SEPTEMBER, 2020



Close-up of the Compact Linear Collider prototype, on which the electron FLASH design is based (Image: CERN)

Geneva and Lausanne. CERN and the Lausanne University Hospital (CHUV), in Switzerland, are collaborating to develop the conceptual design of an innovative radiotherapy facility, used for cancer treatment. The facility will capitalise on CERN breakthrough accelerator technology applied to a technique called FLASH radiotherapy, which delivers high-energy electrons to treat tumours. The result is a cutting-edge form of cancer treatment, highly targeted and capable of reaching deep into the patient's body, with less side-effects. The first phase of the study reaches conclusion this September.

link

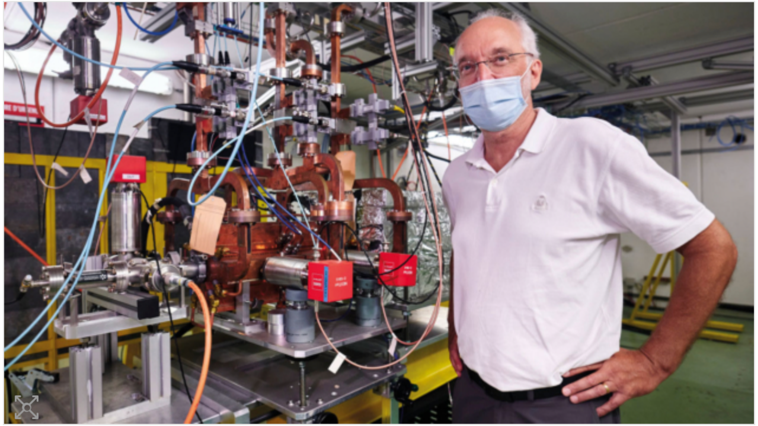
C | Physics ▾ | Technology ▾ | Community ▾ | In focus | Magazine

APPLICATIONS | FEATURE

Adapting CLIC tech for FLASH therapy

15 December 2020

A collaboration between CERN and Lausanne University Hospital will see technology developed for the proposed Compact Linear Collider (CLIC) drive a novel cancer radiotherapy facility.



Technology transfer CERN FLASH study-leader Walter Wuensch in CERN's high-accelerating gradient test area with CLIC accelerating structures, specially adapted versions of which will drive a high-performance accelerator for a future clinical facility. Credit: CERN-PHOTO-202008-108-16

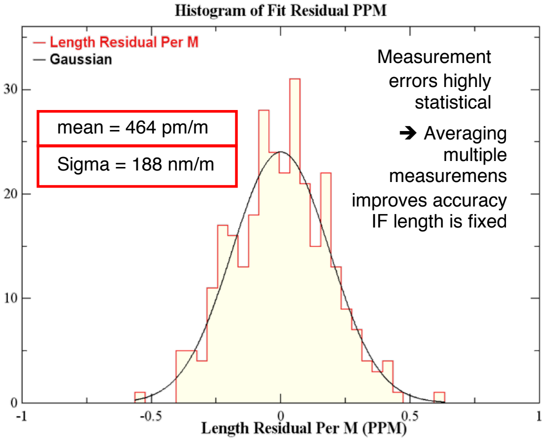
https://cerncourier.com/a/adapting-clic-tech-for-flash-therapy/

JAI Interferometry Capabilities

John Adams Institute for Accelerator Science

A. Reichold

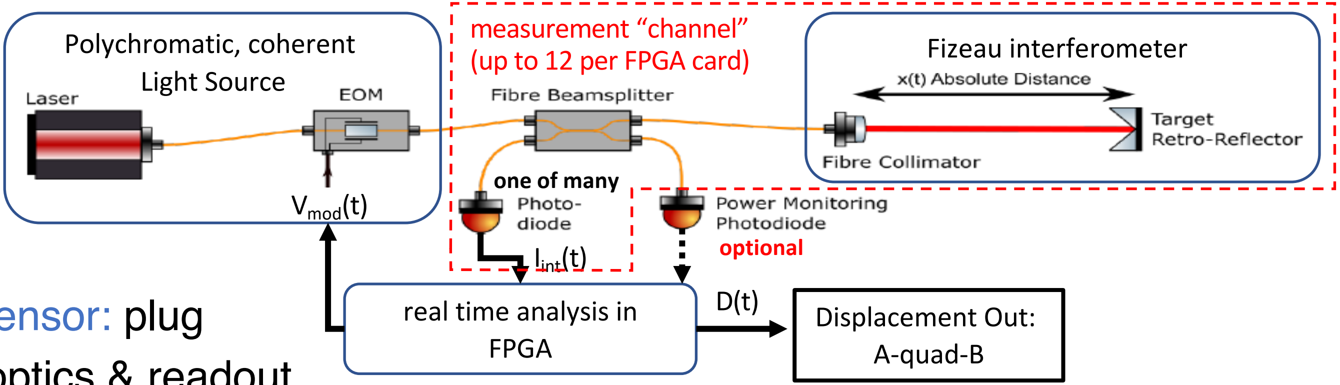
- 2nd Generation absolute distance interferometry
- ***Product*** = Absolute Multiline™ Interferometry
- ***FSI*** = Frequency Scanning Interferometry
- Up to ***124*** simultaneous absolute distance scans
- Range ***0.1m to 30m***
- Absolute uncertainty < ± 0.5 µm/m (95% conf.)
- Scan parameters
  - position resolution < ± 0.1 µm
  - time resolution 125 MHz
  - repetition rate 0.1 to 10 Hz
  - dead time > 0.1 s
  - latency > 1 s
- Target motion < 19 mm/s
- ***Vacuum*** & ***cryogenic*** environments
- One fibre per channel



Current Progress: PaMIr

A. Reichold

Phase Modulation Interferometry



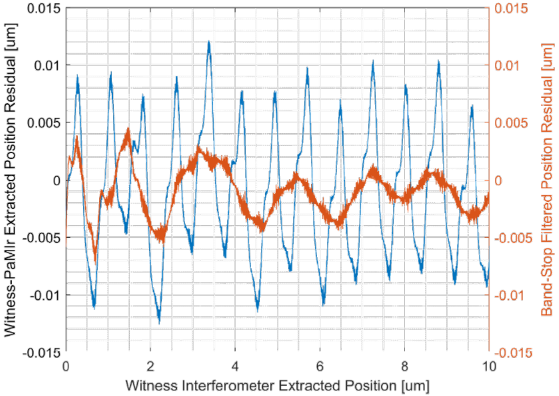
- Real-time Displacement sensor: plug compatible to Multiline™ optics & readout
- 3-year IPS (project start = Feb 2019)
  - £365k STFC-IPS
  - £340k Industry (Etalon + VadaTech)
  - £237k STFC equipment
  - £188k Industry extension (Etalon)
- Team = 2.5 FTE research engineers + PI

- PaMIr details confidential (patent pending)
- Real time signal analysis in FPGA (90% complete)
  - $\Delta T_{lat} < 10$ µs (design)
  - Update rate of A-quad-B 12.5 MHz
  - 12 channels per AMC523 (4 chan. version for Daedalus under consideration)
- Any interferometer ok at any distance 0.1 – 30m
- Simulations: ok at ***1m/s*** target motion

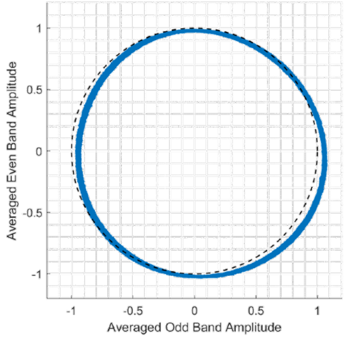
Real Data Results

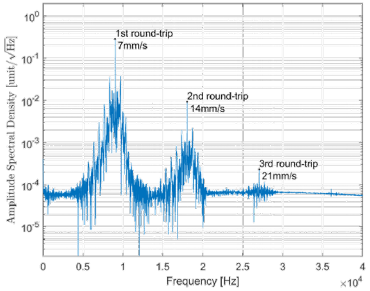
A. Reichold

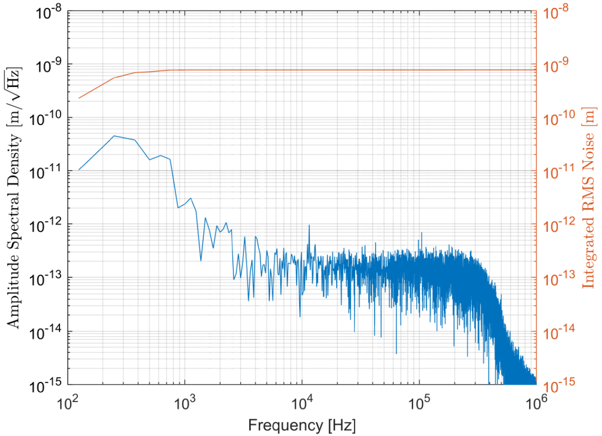
- RMS noise 0.8 nm up to 500 kHz
  - measured on stationary target
  - OPD approximately 1 m
- High quality quadrature signal
- Multiple reflections lead to periodic distortions
- Peak to peak residuals
  - < 25 nm (including full periodic effect)
  - < 12 nm (spectrally filtered)
- Neural-net correction of periodic errors possible
- Hardware suppression of round trips possible



(a) Residual of extracted positions of PaMIr and the witness interferometer. A periodic error with periodicity λ/2 is evident. A multi-band band-stop filter allows to remove contributions of this periodicity. The remaining error is due to noise and mechanical vibrations.







(d) PaMIr extracted displacement noise characteristics. The RMS noise is found by integration from 0 Hz up to the desired cutoff frequency. It approaches 0.8 nm for the full bandwidth of 500 kHz

Commercialisation So Far…

John Adams Institute for Accelerator Science

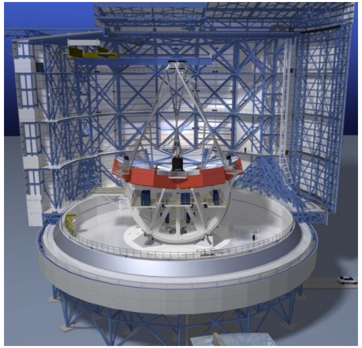
A. Reichold

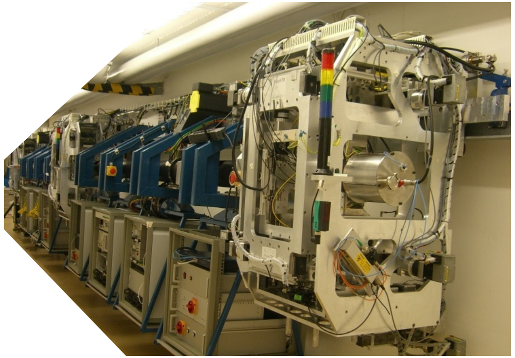
- FSI Patented 2015 ➔ Four licenses to Etalon one to VadaTech
- 1st gen. sales >= 2013, 2nd gen. (µTCA) orders >= 2016
- Sales & orders approx. £5.2M
- Royalties to approx. £300k
- Industrial customers:
  - Siemens Energy - €1Bn off shore wind-energy platform monitoring
  - SAFRAN Reosc - form metrology of 900 EELT mirrors at 20 nm uncertainty
  - DMG Pfronten - thermal CNC machine deformation monitoring
  - Heidenhain - novel calibration methods and thermal CNC monitoring
- Other Research customers
  - NARMC - UK's Nuclear Advanced Materials Research Centre: facility wide CNC and CMM machine calibration network
  - RWTH Aachen Machine Tool Lab - deformations of CNC machines
  - University of Dresden - deformation of robots, presses, tools
  - PTB (Physikalisch Technische Bundesanstalt) = Campus wide distribution network ➔ test rig for mobile metrology instruments, large ultra-precision CMM; deformations in wind energy, torque-test stand
- Accelerator customers:
  - 2 x CERN - in-vacuum alignment of high luminosity LHC crab cavities and quadrupoles
  - 2 x SLAC - alignment of undulator magnets at LCLS-II
  - GSI - a general purpose instrument
  - PSI - in vacuum form measurement & alignment of X-ray mirrors for MAX IV synchrotron
  - Argonne - monitoring of x-ray laser components
  - IHEP China - Monitoring of Accelerator components
- Astronomy customers:
  - GMT - Giant Magellan Telescope: align primary to secondary mirror
  - LBT - Large Binocular Telescope: align primary to secondary, increases usable observation time by 30 minutes per night
  - ESO - European Southern Observatory: mirror deformation measurement and alignment of Harmoni instrument in cryostat
  - SRT - Sardinian Radio Telescope: Monitoring of secondary mirror
  - Russian Academy of Science - cryogenic, in-vacuum deformation tests for Millimetron Space Telescope
  - CCAT - Cerro Chajnantor Atacama Telescope: measure form of 6m x 6m primary in situ, align prim. to secondary, uncertainty <= 5 μm

A Virtuous Circle of Metrology

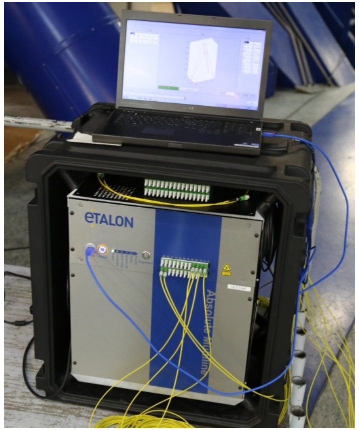
A. Reichold

GMT primary vs. secondary Alignment

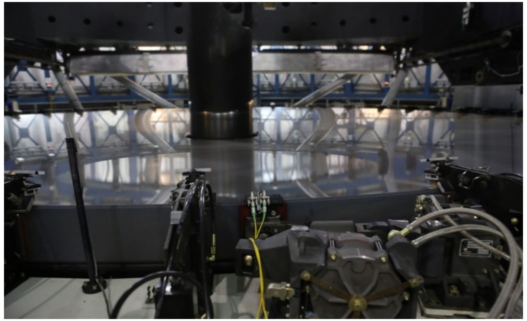




Robotic Tunnel Reference Surveyor (ILC)

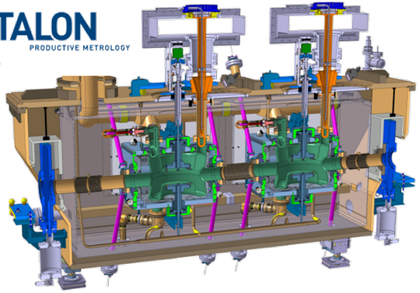


FSI Tech. Transfer to ETALON



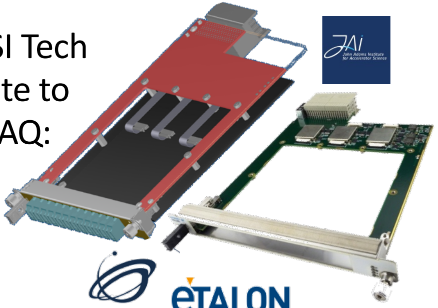
VLT alignment prototyping by ETALON

one example



HL-LHC crab cavity alignment

FSI Tech Update to µTCA DAQ:



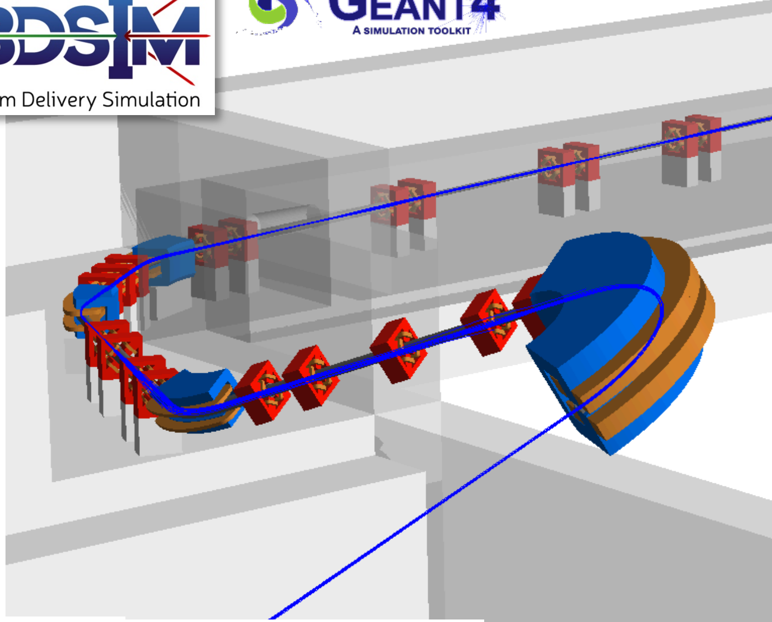
Beam Delivery Simulation (BDSIM)

L. Nevay, W. Shields, S. Boogert

BDSIM Beam Delivery Simulation

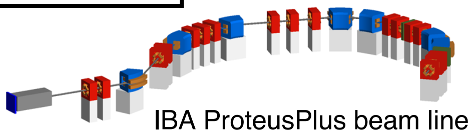
GEANT4 A SIMULATION TOOLKIT

- Idea in 2004 by G. Blair at Royal Holloway for Linear Collider muon backgrounds
    - re-developed and modernised since 2014 by L. Nevay, S. Boogert, W. Shields and RHUL group
- Automatic Geant4 models of accelerators
- Applied to many experiments and machines
    - ***ILC / CLIC***, ***AWAKE, XFEL*** *undulators,* ***LHC*** *collimation,* ***Laserwires, ATLAS*** *non-collision backgrounds,* ***MAGIX*** *at* ***MESA,*** *and recently* ***FASER, KLEVER, NA62 (PBC)***
- Strong application for ***medical therapy systems***
    - including radiobiological research facilities - e.g. LhARA

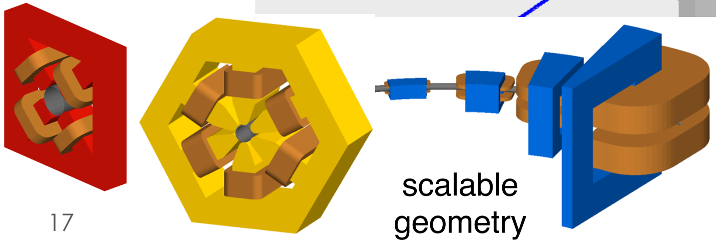


PSI Gantry 2 model

Computer Physics Communications (252), July 2020, 107200



IBA ProteusPlus beam line



scalable geometry

ROYAL HOLLOWAY UNIVERSITY OF LONDON

Proton Therapy Evolution

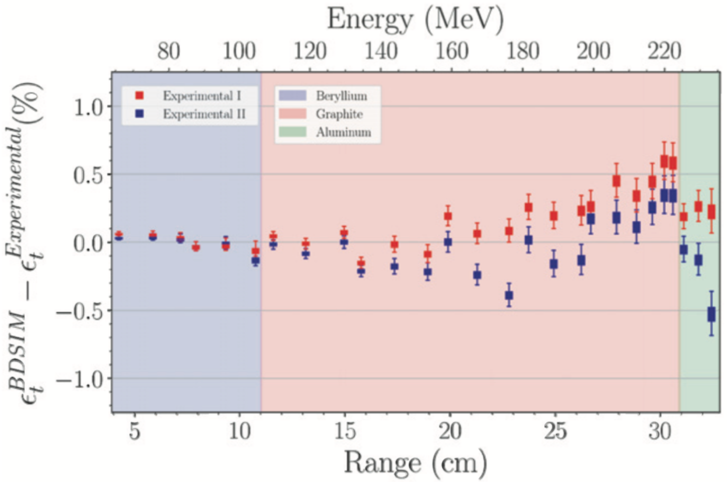
L. Nevay, W. Shields, S. Boogert

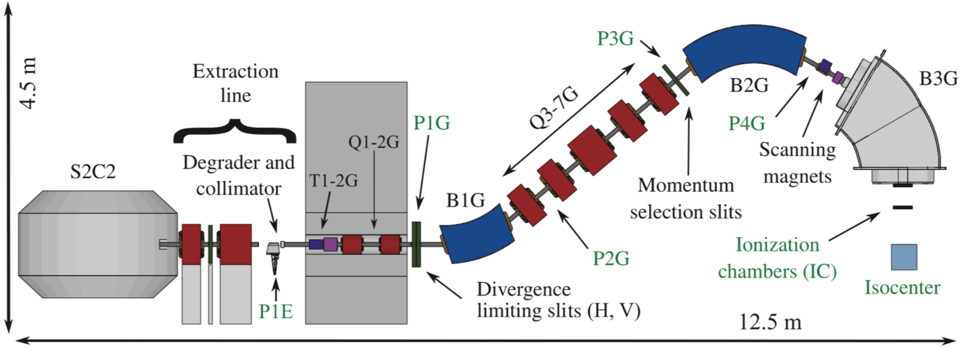
- Vendors are looking to create more compact facilities
  - reduced cost and therefore greater accessibility to meet societal needs
- More compact machines couple patient environment to accelerator one
- Traditional modelling methods (point sources of losses) break down
- Apply BDSIM's ability to create detailed radiation transport models with rich understanding in much smaller times
- Validate against current facilities then apply to new, compact designs

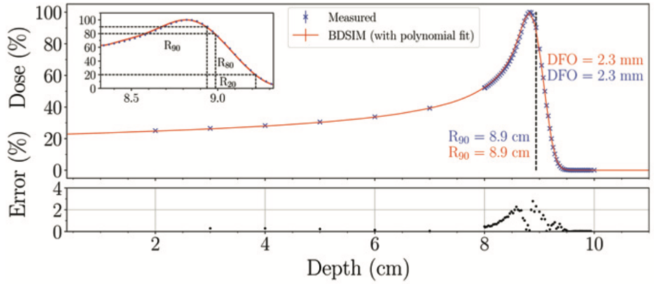
BDSIM Model of IBA Proton Therapy

L. Nevay, W. Shields, S. Boogert

- In collaboration with ULB & IBA we simulated their Proteus One system
- NDA in place between RHUL, IBA & ULB since 2018
- Beam launched from exit of cyclotron
  - interaction in material throughout including degrader
- Excellent agreement in Bragg peaks in water phantom
  - start-to-end simulation
- Further developments underway for *DICOM X-ray CT* loading and 4D scoring







[C. Hernalsteens, L. Nevay et al., European Physics Letters, 132 (2020) 50004]

Further Industrial Applications

S. Boogert, S. Gibson, L. Nevay, W. Shields

- Grant applications: STFC CLASP, EPSRC Research Software Engineering Fellowship, Marie Curie @ ULB
  - impact acceleration funding supporting this activity, ***£68k***
- S. Boogert: studentship co-funded with Public Health England
  - proton therapy quality assurance market
  - 50/50 PHE / RHUL funding for part-time PhD, 6Y
  - former RHUL undergraduate applicant in place
- Other potential industrial collaborations of RT simulations
  - space: advanced geometry modelling capabilities
  - particle transport at industrial levels e.g. RSim

LhARA

- Work beginning with Corerain & Maxeler
  - software companies
- Dose deposition imaging and automation
- Leo Cancer Care
  - medical equipment provider
- Automated positioning

Imperial College London
Department of Physics
Faculty of Medicine

ICR The Institute of Cancer Research
Medical Research Council
UKRI Oxford Institute for Radiation Oncology
University of Oxford
John Adams Institute for Accelerator Science
CCAP Centre for the Clinical Application of Particles
Imperial College Academic Health Science Centre
Cancer Research UK | Imperial Centre
NHS Imperial College Healthcare NHS Trust

Manchester 1824 The University of Manchester
University of Birmingham
Queen's University Belfast
University of Liverpool
Lancaster University
University of Strathclyde Glasgow Department of Physics
UCL Medical Physics & Biomedical Engineering
Royal Holloway University of London

NHS University Hospitals Birmingham NHS Foundation Trust
NHS The Clatterbridge Cancer Centre NHS Foundation Trust
institut Curie
UKRI Science and Technology Facilities Council
ASTeC
Particle Physics Department
ISIS Neutron and Muon Source
INFN Catania
Central Laser Facility

Swansea University Prifysgol Abertawe
University of Birmingham | Positron Imaging Centre
University of Birmingham | Cyclotron Facility
Corerain
The Rosalind Franklin Institute
NPL National Physical Laboratory
The Cockcroft Institute of Accelerator Science and Technology
University of Surrey Ion Beam Centre
LEO Cancer Care
Maxeler Technologies Maximum Performance Computing
LhARA Laser-hybrid Accelerator for Radiobiological Applications

Additional Oxford Commercialisation Activity

John Adams Institute for Accelerator Science

- Spin-outs from the P. Norrey's group from research on plasma wakefield acceleration:
  - ***Living Optics (2020)*** https://livingoptics.co/ is redefining hyperspectral imaging via an algorithmic approach, improving efficiency, resolution and enabling unprecedented miniaturisation: 13 employees, ***£XM raised***.
  - ***Machine Discovery (2019)*** https://machine-discovery.com/ develops and commercialises acceleration and optimisation software for quantum physics: 3 employees, ***£XM raised***.
- STFC IAA Funds*:*
  - funded a project to hold an international workshop on "Growing a UK network to realise impact for a robust medical LINAC for challenging environments" - ***£17,600*** (Event impacted by COVID-19, see presentation from Manjit Dosnah)
- Entrepreneurship Training from Physics DPhil Students:
  - 7-week course delivered by physicists-turned entrepreneurs on how to apply physics research to commercialisation. Course was oversubscribed with 25 students completing the assessment.
- *"I think that physics and entrepreneurship go hand-in-hand, as the cutting-edge ideas and techniques researched in physics often have the potential to solve societal problems. It was also great to form a team with other physicists and get to know them, as well as develop our ideas alongside the formal teaching we had each week."* ***Laurence Wroe, JAI Student***
- https://www2.physics.ox.ac.uk/blog/alumni/2021/01/27/student-entrepreneurs

John Adams Institute
for Accelerator Science

Thank you for your attention