John Adams Institute for Accelerator Science

Education & Training in Accelerator Science

Student Handbook
and Programme Syllabus

2023-2024

September 2023

John Adams Institute for Accelerator Science

The John Adams Institute for Accelerator Science (JAI)

The John Adams Institute for Accelerator Science (JAI) is a centre of excellence in the UK for advanced and novel accelerator technology, providing expertise, research, development and training in accelerator techniques, and promoting advanced accelerator applications in science and society. The JAI programme is organised around three pillars: research in accelerator science; training the next generation of accelerator scientists; and science outreach to industry and the public. The JAI is jointly hosted by the physics departments of the University of Oxford, Royal Holloway, University of London and Imperial College London.

What the JAI Does

The next generation of particle physicists needs the next generation of particle accelerators. The JAI is a UK and world-leading research group dedicated to the research and development of particle accelerators.

We are working on the next generation colliders – the Future Circular Collider (FCC), including the Higher-Energy LHC (HE-LHC), and the linear colliders of the Compact Linear Collider (CLIC) and International Linear Collider (ILC) collaborations. These machines may become the next particle accelerators designed to complement the discoveries made at the Large Hadron Collider (LHC) and its high-luminosity upgrade (HL-LHC) at CERN.

Modern light sources, synchrotron-based and free electron lasers, are indispensable for scientific and technological development of the modern economy and society. We are working on improving light sources such as Diamond, and working on further ideas.

A very challenging, but very promising direction is the creation of compact light sources and accelerators for particle physics based on laser plasma acceleration. The JAI has a unique combination of research teams working together to address this challenge, see in particular the pages of Simon Hooker's team at the University of Oxford and the pages of JAI at Imperial. JAI is participating in the AWAKE experiment and is also a member of the Helmholtz Virtual Institutes and the EUPRAXIA project.

In addition to the high-energy frontier, accelerators are also required at the so-called 'intensity' frontier, usually providing very high-power beams of hadrons in order to produce secondary particles such as neutrons, muons or neutrinos. This research area addresses upgrades to existing machines (including the LHC) to increase the intensity, as well as research to understand fundamental properties of beams at high intensity using a scaled experiment called 'IBEX'. This could lead to breakthroughs in hadron beam accelerators leading to better scientific facilities, easier access to radioisotopes in medicine or even methods to reduce the lifetime of nuclear waste through accelerator driven transmutation. Within this context, JAI is contributing to the Physics Beyond Colliders initiative at CERN and to the ISIS neutron and muon source (including its upgrade).

Large particle accelerators for particle physics make up just a handful of the 35,000 accelerators in the world. Smaller particle accelerators are used in applications closer to home, such as in medicine, industry and archaeology. In particular, JAI collaborates with institutes in the UK and internationally on the development of particle accelerators for the treatment of cancer.

The JAI Graduate Accelerator Physics Programme

Accelerator Physics Course

Term I (Michaelmas Term 2023)

This is the first half of a series to be completed in Term II (Hilary Term 2024). The format in Michaelmas Term 2023 is 24 one-hour lectures supplemented by six two-hour Tutorials. The course includes a basic grounding in particle accelerators (transverse and longitudinal dynamics, beam imperfections, RF acceleration, beam diagnostics & instrumentation, and synchrotron radiation) as well as in plasma physics and lasers to prepare students for the development of laser-driven devices for particle acceleration.

The aim of the tutorials is to show the students how to use standard simulation and design software tools which calculate important design features of an accelerator. Specialists in the fields of machine lattice, cavities and magnets will lead the classes. At the end of each class students should be able to run simple data input sets for each program.

Lecture Programme

Types of Particle Accelerators

This lecture provides an overview of the development of accelerators throughout history, including some of the key innovations such as phase stability and focusing principles. After this lecture, students should be able to explain the basic operating principles of a range of different types of accelerators, including electrostatic accelerators, linear accelerators, cyclotrons, synchrotrons and fixed-field alternating-gradient accelerators.

Applications of Accelerators

This lecture provides an overview of applications of accelerators to a variety of fields. Applications in the fields of particle physics, medicine, industry, and the physical, environmental and life sciences will be highlighted.

Live Connection – LHC Control Centre CERN

This is a special lecture consisting of a live connection with the control centre of the LHC and its injectors at CERN, Geneva and a presentation by a member of the LHC operation crew. It includes an overview of accelerator operations and activities of the operations teams to ensure the performance of the accelerator complex. A summary of key accelerator parameters and their *in-situ* measurement at the LHC will also be given.

Transverse Optics I & II

This series of two lectures gives an introduction to transverse dynamics in periodic accelerators. The first lecture takes students through a treatment of focusing in cyclotrons and weak focusing in synchrotrons, introduces the multipole description of magnetic fields and motivates strong (alternating gradient) focusing. The second lecture starts by considering the Hamiltonian for particle motion in an electromagnetic field and briefly derives the equation of motion (Hill's equation) and its solution. This lecture introduces the concepts of transfer matrices, stability of focusing, betatron tune, and phase space.

Longitudinal Beam Dynamics and Momentum Effects

This series of two lectures provides an introduction to longitudinal beam dynamics in the periodic accelerators. The lectures include phase stability in a repetitive acceleration system; transition and momentum compaction; and the effect of momentum spread.

RF Cavities (I, II, and III) and RF Cavity Design

The four lectures introduce the principles and design of microwave cavities for acceleration, phase and group velocity, transit time factor and shunt impedance. This series also includes an introduction to the simulation of cavities using specialised software, such as SUPERFISH and CST.

Properties of Synchrotron Radiation, Undulators & Wigglers, Radiation Damping and Radiation Excitation

This series of four lectures concentrates on synchrotron radiation and its effects on electron beam dynamics in storage rings. It includes an introduction to the properties of synchrotron radiation and synchrotron light sources. The series covers in detail the angular distribution of the power radiated by accelerated particles as well as the angular and frequency distribution of the radiated energy. It also covers the physics principles of radiation from wigglers and undulators.

Accelerator Plasma Physics I,II,III

This series on accelerator plasma physics consists of three lectures. The series provides basic concepts in accelerator plasma physics, an introduction to laser-plasma-based ion accelerators and an introduction to plasma wake-field accelerators. The lectures will allow students to identify synergies between particle accelerators, lasers and plasma.

Beams and Imperfections

This lecture introduces topics that result in imperfections in an accelerator design and operation. Topics covered include resonant conditions, closed-orbit distortion, gradient errors, and chromaticity corrections.

Hamiltonian Dynamics I & II

These two lectures give an overview of Hamiltonian dynamics both in general and from the perspective of accelerator physics. The series of lectures start by exploring the relationship between the Hamiltonian, Lagrangian and Newtonian formulation of mechanics. The lectures then cover the key concepts associated with the Hamiltonian approach - including Hamilton's equations, canonical transformation and Hamiltonian-Jacobi theory before shifting focus to accelerator physics. From the Hamiltonian, the equations of transverse dynamics and associated concepts such as Liouville's theorem, action-angle variables and symplectic and chaotic motion are obtained. The lectures also include perturbation theory and its application to the study of nonlinear resonances.

Beam Diagnostics and Instrumentation

This lecture covers introductory topics of beam diagnostic methods and instrumentation for their measurement. It includes topics such as the observation of beam and the measurement of beam current; the beam lifetime in a storage ring; the measurement of the momentum and energy of a particle beam; the measurement of the transverse beam position; and the measurement of beam optical parameters.

Parameters for Student Project Design

This lecture introduces the Student Design Project of Term II (Hilary Term 2024), which is based on the Laser-hybrid Accelerator for Radiobiological Applications (LhARA) facility. LhARA is conceived as dedicated facility for the study of radiobiology. It will be a hybrid accelerator system in which laser interactions drive the creation of a large flux of protons or light ions that are captured using a plasma (Gabor) lens and formed into a beam. The laser-driven source allows protons and ions to be captured at energies significantly above those that pertain in conventional facilities, thus evading the current space-charge limit on the instantaneous dose rate that can be delivered. It is proposed that LhARA be developed in two stages. In the first stage, a programme of *in vitro* radiobiology will be served with proton beams with energies between 10 and 15 MeV. In stage two, the beam will be accelerated using a fixed-field alternating-gradient accelerator (FFA). This will allow experiments to be carried out *in vitro* and *in vivo* with proton beam energies of up to 127 MeV. In addition, ion beams with energies up to 33.4 MeV per nucleon will be available for *in vitro* and *in vivo* experiments. The lecture presents a concise description of the layout and parameters of the LhARA and discusses the main accelerator physics and technology challenges that will be studied further in Term II (Hilary Term 2024).

Tutorials

Six Exercise Papers are due for Term I (Michaelmas Term 2023) and will be marked as part of the course assessment. Students should submit their answers to the Exercise Papers at the tutorials according to the following schedule:

1. Introduction to Accelerators (Week 2)
2. Transverse Optics (Week 4)
3. Longitudinal Dynamics (Week 5)
4. RF Cavities (Week 7)
5. Hamiltonian Dynamics (Week 8)
6. Synchrotron Radiation (Week 8).

Term II (Hilary Term 2024)

In Term II (Hilary Term 2024), topics which will be covered in the lectures are: magnet design, non-linear dynamics, space-charge effects, beam-beam effects, linear colliders & free-electron lasers, beamlines for fixed-target experiments, cyclotrons for various applications, radiobiology & accelerator science applications, vacuum & surface science, injection, transfer lines & extraction, and particle sources.

The lectures will be supplemented by weekly tutorials that will apply the skills learned in the first term to prepare the Student Design Project for the study of a new accelerator. Participating students will hand in draft chapters of different parts of a design report for marking at each of the tutorials.

For 2023-2024, the Student Design Project will be on the Laser-hybrid Accelerator for Radiobiological Applications (LhARA) facility. LhARA is conceived as dedicated facility for the study of radiobiology. It will be a hybrid accelerator system in which laser interactions drive the creation of a large flux of protons or light ions that are captured using a plasma (Gabor) lens and formed into a beam. The laser-driven source allows protons and ions to be captured at energies significantly above those that pertain in conventional facilities, thus evading the current space-charge limit on the instantaneous dose rate that can be delivered. It is proposed that LhARA be developed in two stages. In the first stage, a programme of in vitro radiobiology will be served with proton beams with energies between 10 and 15 MeV. In stage two, the beam will be accelerated using a fixed-field alternating-gradient accelerator (FFA). This will allow experiments to be carried out *in vitro* and *in vivo* with proton beam energies of up to 127 MeV. In addition, ion beams with energies up to 33.4 MeV per nucleon will be available for *in vitro* and *in vivo* experiments. Aspects of the lattice, magnet system RF acceleration and the plasma devices of LhARA will be studied as part of the design. The students will prepare a Design Report and deliver a JAI Seminar on their study.

Lecture Programme

Magnet Design (I, II) and Demonstration of Magnet Design Program

The lectures will introduce magnets as building blocks for accelerators and will focus on their use in synchrotrons and transfer lines. Following an overview of the various types of magnets, the lectures will cover the nomenclature and mathematical concepts underpinning the various types of magnets. This will be followed by coverage of the basics required for the design of resistive magnets and of superconducting magnets. The demonstration class will provide the opportunity for students to carry out first magnetic simulations with the FEMM software package.

Non-Linear Dynamics (I, II)

The two lectures on non-linear dynamics will cover the fundamental physics and mathematics principles required to understand and analyse the stability of particle beams in accelerators. A number of topics to this effect will be covered, including non-linear magnetic multipoles, the phenomenology of nonlinear motion, a simplified treatment of resonances (stopband concept), the Hamiltonian of the nonlinear betatron motion, resonance-driving terms, tracking, dynamic aperture and frequency map analysis, and spectral lines and resonances. The lectures will conclude with the description of some non-linear beam dynamics experiments performed at the Diamond Light Source.

Linear Colliders (I, II, III, IV)

The series of four lectures on linear colliders will focus on the design of future linear colliders at the high-energy frontier. The lectures will explain the fundamental lay-out of a linear collider and the specific designs based on normal-conducting and superconducting technologies. It will also include a discussion on some of the driving forces and limitations in the design of a linear collider. The lectures will commence with an introduction providing an overview to linear collider scaling principles and the two candidates for future linear colliders – the Compact Linear Collider (CLIC) and the International Linear Collider (ILC). This will be followed by detailed coverage of the corresponding various sub-systems, including the particle source, the damping rings, the bunch compression and the main linear accelerators. The lectures will also include a discussion on topics such as wakefields, acceleration and alignment as well as the design beam parameters.

Beam Injection, Transfer Lines and Extraction

The lecture covers beam injection, transfer and extraction focusing on various aspects of particle injection, transfer and extraction and introduces the state-of-the-art techniques of hardware components used in modern accelerators. The lecture will cover the injection methods - single-turn hadron injection, injection errors, filamentation blow-up, multi-turn hadron injection, charge-exchange H- and lepton injection. This will be followed by the extraction methods - single-turn (fast) extraction, non-resonant and resonant multi-turn (fast) extraction and resonant multi-turn (slow) extraction. The lecture will also cover aspects of beam transfer and transport, providing the mathematical underpinnings and formalisms for transfer lines and discussing the matching of optics functions for transfer lines.

Particle Sources

Following an introduction providing background to the fundamental processes underlying the production of particle beams, the lecture will cover the various types of particle sources and associated technological issues as well as the various applications for which particle sources are used. The lecture will also probe the process by which particle sources are chosen for specific applications, their reliability and strategies for the development of sources for future applications.

Instabilities (I, II)

This series of two lectures will provide an introduction to beam instabilities, focusing on their causes and mitigation measures. The lectures will provide a general overview defining instabilities, an introduction to impedance considerations, the general method for studying instabilities and the effect of Landau Damping. The lectures will explain how broad-band impedances are responsible for single-bunch instabilities and narrow-band impedances can cause multi-bunch instabilities. It will be shown that both types of impedances can cause longitudinal as well as transverse instabilities.

Beam-Beam Effects

This lecture will provide an introduction to the beam-beam effect and will show that the beam-beam effect is one of the main limiting effects in modern accelerators. The lecture will cover the linear beam-beam parameter ξ and long-range interactions. Some insights into the non-linear effect will also be given, although this effect does not yet have a fully consistent underlying theoretical foundation. Measures to be taken to mitigate beam-beam effects will also be presented.

Space Charge Tune Shift

This lecture will provide an introduction on space-charge tune-shift effects. It will cover space charge forces, space charge in transfer lines, image effects, incoherent versus coherent tune shift effects in synchrotrons and will also provide a number of examples of space charge tune shift effects in particle accelerators. Rigorous treatment of coherent and incoherent space-charge effects will be provided, showing that a high-intensity, un-bunched beam experiences a small deflection by a kicker magnet in one plane and performs betatron oscillations.

Beamlines for Fixed-target Experiments

The lecture provides an overview of the past and current fixed-target experiments and their beamlines. The conceptual description of the secondary and tertiary beams for the fixed-target experiments and for the use as test beams is given. It includes the generation of the secondary beams through the interaction of a primary beam with a target, converter, radiator or absorber, and it explains the parameters of particle production. The design of secondary and tertiary beamlines is presented, comprising the methods for selection of particle type and beam energy, as well as for the manipulation of beam parameters such as beam size, divergence, intensity etc. A brief summary of beam diagnostic tools and their functionality is also given.

Cyclotrons for Various Applications

In this lecture, the operation of the cyclotron will be discussed in detail. Apart from the classical cyclotron, the separated sector cyclotron and the synchrocyclotron will also be treated. The effects of the major subsystems on the beam and the acceleration will be illustrated. Together with the magnetic field system, the RF system, ion source and extraction methods, the lectures will also discuss the processes involved in isochronicity, betatron oscillations and beam dynamics aspects, as well as the effects of space charge at high intensities. In addition, the different types of cyclotrons for specific applications will be compared to each other.

Free Electron Lasers

This lecture will provide an overview of Free Electron Lasers (FELs). It will cover the basic requirements on linear accelerators. Undulators and the process of lasing and seeding will then be treated in some detail and will be followed by an explanation of the various beam dynamics and beam control issues. The lecture will also present the various FELs in operation today and provide the important features of future such machines.

Vacuum and Surface Science

The lecture will provide an introduction to vacuum systems required in particle accelerators and the associated surface science issues. The lecture will focus on vacuum requirements for accelerators and the effects of failing to meet these requirements; the critical parts of an accelerator vacuum system – including pumps, gauges, seals, control and diagnostic systems; and the challenges encountered with designing vacuum systems – suitability of materials, vacuum cleaning and manufacturing specification, software and modelling limitations. A brief summary of general surface science techniques such as Auger electron spectroscopy, photo-electron spectroscopy and Secondary Ion Mass Spectrometry will also be provided.

Accelerator Science and Particle Therapy

This lecture will provide an introduction to the application of accelerator science in particle therapy. The lecture will cover the following topics : the Bragg peak ; momentum variation and how to generate a Spread Out Bragg Peak as well as momentum selection systems ; transverse dose distribution ; scattering according to the Bethe-Bloch formula for energy loss and the Moliere formula for multiple scattering ; the design of scattering foils and range compensators ; pencil beam scanning ; Intensity Modulated Hadron Therapy ; range straggling ; organ motion together with possible solutions; and beam possible facility types and gantry layouts.

Introduction to Radiation Biology and its Applications in Accelerator Science

This lecture provides an introduction to radiation biology with a particular emphasis on aspects of direct relevance for its applications in accelerator science. The lecture will cover the types of ionising radiation, the linear energy transfer (LET), the relative biological effective (RBE), mechanisms of DNA damage and repair, cell survival curves, cell cycle, and dose-response relationships, dose-fractionation, and different radiation modalities. The lecture will also address how radiation treatment is determined by the 4 Rs of radiobiology: repair of DNA damage, redistribution of cells in the cell cycle, repopulation, and reoxygenation of hypoxic tumor areas.

Course Resources

The course resources are available here and include the lecture timetables, slides and documents as well as information on the video conferencing connection.

Education Visit to CERN

As part of the graduate course, a visit to CERN is organised at the end of the Student Design Project. The visit programme includes tours of the accelerator facilities of the Laboratory, including the LHC and other accelerator facilities that groups from the JAI and its member universities participate. The visit to CERN also includes a presentation by the students of their design project at a seminar to expert accelerator physicists. Students should make their research supervisors aware of this and advise the course lecturers of any unavailable periods between March and June 2024 in order to assist with the planning.

Assessment

The graduate course Accelerator Physics consists of six compulsory Exercise Papers in Term I (Michaelmas Term 2023) and a Student Design Project in Term II (Hilary Term 2024). The six Exercise Papers have equal weighting that make up the overall mark for Term I (Michaelmas Term 2023). The Student Design Project is examined along the following four criteria with the relative weighting and makes up the overall mark for Term II (Hilary Term 2024):

- Introduction Exercise Paper (15%)
- Development of Design Project (40%)
- Final Report (30%)
- Seminar Presentation (15%).

Further general information for graduate students is available at:

University of Oxford

Imperial College London

Royal Holloway, University of London

Course Evaluation

Students will be invited to provide feedback on the course. This includes a presentation of their work to the next meeting of the JAI Advisory Board, which is expected to be held in April 2024. Students will have the opportunity to discuss their course experience with the members of the JAI Advisory Board. A questionnaire will also be sent to all students for further feedback.

Lecturers and Tutors

Term I - Michaelmas Term 2023

Dr. Hector Garcia-Morales (Oxford)
Dr. David Kelliher (Rutherford Appleton Laboratory)
Dr. Stuart Mangles (ICL)
Dr. Ian Martin (Diamond Light Source)
Prof. Zulfikar Najmudin (ICL)
Dr. Ciprian Plostinar (European Spallation Source)
Prof. Emmanuel Tsesmelis (CERN & Oxford)
Dr. Rob Williamson (Rutherford Appleton Laboratory)

Term II - Hilary Term 2024

Prof. Manjit Dosanjh (Oxford)
Dr. Matthew Fraser (CERN)
Dr. Alexander Gerbershagen (CERN)
Dr. Scott Lawrie (Rutherford Appleton Laboratory)
Dr. Ian Martin (Diamond Light Source)
Dr. Attilio Milanese (CERN)
Dr. Sunil Patel (Rutherford Appleton Laboratory)
Dr. Ciprian Plostinar (European Spallation Source)
Dr. Marco Schippers (Paul Scherrer Institute)
Dr. Frank Tecker (CERN)
Prof. Emmanuel Tsesmelis (CERN & Oxford)

Recommended Textbooks

The underlying texts are *An Introduction to Particle Accelerators* by Edmund Wilson (OUP) IBSN 0 19 850829 8 and *Unifying Physics of Accelerators, Lasers and Plasma* by Andrei Seryi (CRC Press) ISBN 978-1-4822-4058-0.

Engines of Discovery by Andrew Sessler and Edmund Wilson (WSP) IBSN 978-981-270-071 and *Engines of Discovery – Revised and Extended* by Andrew Sessler and Edmund Wilson (WSP) ISBN 978-9814417198 are recommended as background reading.

Additional textbooks and reading recommendations for specific sub-topics will be supplied by the course lecturers during term.

Summer Studentships

Oxford University Internship Programme (to CERN)

Interns in their 3rd year of their 4-year course in Physics or Engineering are invited to apply to the Oxford University Internship Programme (to CERN) in 2024. The selected students will attend the CERN Summer Student Programme lectures and work on an accelerator-based project.

Oxford Summer Student Placement

The JAI is providing summer project opportunities at Oxford - see this link for the Summer Placement Programme.

Public Engagement

Accelerate! Show

The *Accelerate! Show* is an award-winning, live, interactive science show aimed at audiences of high school pupils. The show uses a series of exciting demonstrations from exploding hydrogen balloons and liquid nitrogen with levitating superconductors through to giant beach balls - all to tell the story of how particle accelerators work. All JAI students are welcome to join the team to learn to present the show (or help backstage, if you do not like to be in the spotlight), and to learn how to safely perform some fantastic demonstrations and gain confidence in your presenting ability. Past presenters are regularly invited to speak at high-profile events and on TV and radio. The script, demonstration and information are available online. Students are more than welcome to adapt the show to their own research interests. Contact Dr. Suzie Sheehy for more information.

The Big Bang Experience! A brief history and future of the LHC

If you have watched the characters in The Big Bang Theory TV show, then you may think of particle physicists as an odd bunch: why do boffins spend their time in huge underground laboratories like CERN accelerating particles in endless circles like an enormous train set? How do you get a train of particles to nearly the speed of light anyway, and why would you want to? What happens when the particles collide? Might anything go wrong? Or could a particle accelerator one day save your loved one's life?

Find out! Join Royal Holloway's Particle Accelerator Physicist Dr. Stephen Gibson, and friends, as they guide you with live demonstrations on the wonders of the Large Hadron Collider, and how it is unlocking the secrets of nature. Learn why it was built, how it works and how Dr Gibson's team are helping to stop it self-destruct (again) in an explosion of liquid helium!

Further information is available here.

Accelerator and Particle Physics Education at A-Level (APPEAL)

Since 2010, the JAI organises in collaboration with CERN a one-day annual school to give A-level teachers an opportunity to learn about the phenomena and scientific challenges which connect astrophysics, particle physics and the physics of particle accelerators. This school is designed for physics teachers who are not necessarily physics specialists. Preference will be given to teachers coming from schools which usually send very few pupils to University.

The schools address questions such as "How does a particle accelerator work?" "What are the questions the LHC will answer?" "How does an experiment at the LHC work?" "What are the applications of particle accelerators in our daily lives?" and "What is the origin of the Universe and of matter?"

Further information is available on the APPEAL site here.

JAI Events

JAIFest – The full day annual JAIFest held at the end of Term I (Michaelmas Term 2023) includes presentations from academic staff and graduate students. Graduate students are expected to attend. The next JAIfest will be held in December 2023.

UK Accelerator Institutes Seminar Series – The series of seminars are delivered by distinguished lecturers from the three UK institutes ASTeC, Cockcroft Institute and JAI and from laboratories / universities world-wide. The seminars are scheduled so that the graduate student body can attend. Further information is available here.