BRITISH ACCELERATOR SCIENCE AND RADIATION ONCOLOGY CONSORTIUM (BASROC)

The Non-Scaling Fixed Field Alternating Gradient accelerator

A revolutionary accelerator design for science, medicine and industry

There are over 17,000 particle accelerators worldwide, with fewer than 200 used for purely scientific research (particle and nuclear physics, synchrotron radiation and neutron spallation); most are used in medicine and industry. There is an urgent need for accelerator designs that are cheaper to build, more robust and flexible, compact and easier to operate. The novel Non-Scaling Fixed Field Alternating Gradient (NS-FFAG) accelerator should satisfy this need and looks ideal for a wide range of applications:

- *in* ***basic research*** *to study the origin of matter and the evolution of the Universe, and to produce neutrons for structure of materials studies;*
- *in* ***cancer treatment*** *for rapid, safe and economical therapy of deep or awkwardly sited cancers in as many regional centres as required;*
- *in* ***industry****, to design advanced materials and electronic devices;*
- *in* ***safe nuclear energy*** *generation and* ***disposal of nuclear waste****.*

Investing in the R&D for an NS-FFAG would put the UK at the forefront of accelerator technology.

1. Proposal

The NS-FFAG combines the best characteristics of the two accelerator designs used by industry and hospitals for many applications - the flexibility of the synchrotron, with the stability, high intensity and relative simplicity of the cyclotron. It has the potential to bring a sea-change in accelerator technology. However, no-one has yet built such a machine, and realising its potential poses many challenges. The proposal is to design and build: (i) a proof-of-principle demonstration NS-FFAG that would accelerate electrons (EMMA) to understand its basic behaviour; (ii) a low-energy proton version (PAMELA) for particle beam oncology studies - a practical demonstration of the technology. A specific aim is to do the R&D to design of a full-scale radiation therapy facility (for which funding would be sought from cancer charities, the NHS and industry).

2. How it works

The FFAG has a fixed magnetic field for bending and focusing the particle beam, like a cyclotron, but the strength of the magnetic field varies with radius to keep the particles in the machine as they are accelerated. It employs 'alternating gradient focusing' whereby an alternating arrangement of inward and outward magnetic fields keeps the beam focused, as in a synchrotron. This means the accelerator ring is more compact than for a cyclotron. FFAG designs developed so far (in Japan) have large and complex magnets. There is now great interest in Europe and North America in a radically novel design where particle orbits grow much less, reducing the size and cost of the accelerator components, particularly magnets; this is the **Non-Scaling FFAG**.

3. Advantages of Non-Scaling FFAGs

The NS-FFAG combines the simplicity of the cyclotron (the fixed field) with the flexibility of the synchrotron (variable energy). Its features are shown in the table below.

▪ Rapid cycling time	▪ High intensity beams
▪ Small beam losses	▪ Highly compact
▪ Reliable	▪ Accelerate to high energies
▪ Easy to maintain and operate	▪ Accepts a wide range of energies and angles
▪ Beam extractable at different energies into several beam lines	▪ Can accelerate both protons and heavier ions

The relatively small size, ease of use, reliability and smallness of the beam losses are especially important for non-research applications.

4. Applications

4.1 *Fundamental research (PPARC, CCLRC)*

A major project being studied internationally is the Neutrino Factory, designed to make intense neutrino beams from the decay of muons. One goal is to search for differences between neutrinos and antineutrinos that could explain why there is very much more matter than antimatter in the Universe. Muon beams, which naturally have a large size and wide spread in energy, must be accelerated and stored. Until recently the only way to accelerate them was thought to be by using costly recirculating linear accelerators. An NS-FFAG would provide a technically superior and cost-effective way to capture and to accelerate the muons that generate the neutrinos.

4.2 *Charged particle beam cancer therapy (MRC, BBSRC)*

Up to half of cancer patients in the UK receive radiation therapy using X-rays. X-rays deposit much of their energy in healthy tissues surrounding the cancer, with potential resultant loss of function and impaired quality of life. Beams of charged particles, protons and carbon ions (especially of variable energy), are much more promising since higher doses can be delivered to cancers while minimising the dose to normal tissue; this is particularly important for cancers situated in close proximity to essential tissues/organs. They are particularly effective at treating cancers impossible to access surgically and where X-ray therapy either produces disappointing results or is not used at all. Clinical results from USA, Germany and Japan are impressive. An NS-FFAG looks to be ideal for such therapy, with considerably shorter treatment times. Experimental radiobiology and fractionation studies and extended clinical use will follow because of the reduced size and costs.

4.3 *Materials research (EPSRC, CCLRC)*

Neutron scattering is an increasingly useful tool for studying the structure and behaviour of commercially important materials. A proton NS-FFAG could generate spallation neutrons for these experiments. In addition, such a proton beam can be used to generate low energy muons for the study of material properties using muon spin rotation. The recently concluded review of the UK neutron strategy Technology Panel identified FFAGs as one of a range of technologies that the UK should develop, where possible in an international environment.

4.4 *Safe energy generation (NERC, EPSRC)*

A novel approach to nuclear power for electricity generation is to use a sub-critical accelerator-driven reactor. This requires the accelerator to be running to produce power, and so offers safety advantages. This technology is also being studied in Europe to burn up long-lived radioactive waste by transmutation, and could benefit from the reliability of an NS-FFAG.

This generic accelerator technology development, if successful, surely will find other widespread applicability due to its uniquely attractive characteristics.

5. The technology challenge

The scaling FFAG is a 40 year-old idea that was not pursued partly because of its technical complexity. Very recently a Japanese team revisited the concept, demonstrating that the technical difficulties could be overcome. They have now successfully constructed and operated two proton FFAGs, at energies of 500 keV and 150 MeV respectively. Now, an even better idea has emerged - the **non-scaling FFAG**. The main difference is that the paths followed by the charged particles do not 'scale' with energy, but the orbit shape changes with the energy changes. While this makes the beam dynamics more complicated, it simplifies significantly the magnetic-field configuration, allowing the machine to be built with simpler, smaller magnets. The price to be paid is that these machines have unique and untested features that demand prototyping before further progress can be made. The main technology challenges are to study these features, learn how NS-FFAGs can be optimised for a variety of applications, and demonstrate that the principal components (magnets, RF, diagnostics, and control systems) can be designed and built with the required characteristics. It is essential now to build demonstrator machines.

The BASROC programme focuses on the design, construction and exploitation of two complementary machines which together address the technical issues that must be solved before the final goals – a full-scale ion therapy machine, and a fast muon accelerator for particle physics – can be realised:

• The Electron Model for Many Applications (EMMA) will be used to study the basic behaviour of NS-FFAGs using relativistic particles at low energies to learn how to optimise designs for different applications.

• The Particle Accelerator for Medical Applications (PAMELA) will study the behaviour of NS-FFAGs working with non-relativistic ions, in particular developing methods for injecting and extracting protons and heavier ions, primarily for particle beam therapy, and also providing a beam for oncology research

6. Benefits to society - the wider picture

6.1 *Healthcare*

Proton and ion therapy is one of the most promising cancer treatments and is expanding worldwide. The one NHS low-energy proton facility – Clatterbridge (Liverpool) – treats eye cancers only. A full ion-therapy centre based on an NS-FFAG would considerably improve the effectiveness of NHS strategies for treatment.

6.2 *Exploiting UK expertise*

The UK has established expertise in building accelerators and their components, and so is well-placed to develop NS-FFAGs. Expertise is focused in several laboratories including two new research centres devoted to innovative accelerator technology.

6.3 *Training*

The project provides an ideal opportunity to train a new generation of scientists and engineers in a wide range of broadly applicable technologies – accelerator design and construction, magnet and RF technology, vacuum engineering, sensors, diagnostics and control.

6.4 *Technology markets*

The successful design, construction and exploitation of EMMA and PAMELA will place the UK among the world leaders in accelerator science, and create opportunities for UK industry. There is a large potential market for a new generation of hospital-based proton and ion accelerators that are more compact, controllable, reliable, and cost effective.

6.5 *Improving the European knowledge base*

NS-FFAGs represent accelerator research at the leading edge, and are already the object of a great deal of interest worldwide, particularly in the US, Japan and Canada. The BASROC projects would inevitably generate partnerships within Europe and provide an opportunity for the UK to lead a major international, interdisciplinary scientific programme with significant economic and societal benefits.

7. In the longer term

A clear aim is that, once the lessons have been learned from the two demonstration machines, a full clinical facility could be built, delivering precisely controlled proton beams at energies up to 300 MeV - with the option of adding a further ring to accelerate heavier ions such as carbon. This would have to be funded by the healthcare sector, and would be developed by industry. The expectation is that eventually a network of ion therapy centres would be set up at major cancer centres throughout the UK. Meanwhile this successful development will stimulate other applications such as their utilisation in research based activities such as a Neutrino Factory or advanced neutron source.

8. Industrial implications and involvement

Given the potential for the non-scaling FFAG in scientific, medical and industrial applications, it is important that the industrial capability is developed along with the accelerator science. We have had informal discussions on these issues with key UK magnet and RF technology companies, who will be responsible for providing the key components, and with the RF Faraday partnership, details of which can be provided upon request under suitable confidentially arrangements. While it is an objective of this bid to place UK industry in a prime competitive position to develop and exploit this technology, it will also be necessary to work with established international partners in this area.

9. Costs

The preliminary estimates of the cost of the project are about £3.8M in equipment, and 29FTE of additional professional staff effort, excluding working margins and contingency.

10. Conclusion

Non-scaling FFAGs are likely to bring about a revolution in accelerator design. They could replace cyclotrons and synchrotrons for many existing applications and open up new possibilities.

This is an opportunity for the UK to take the initiative and lead this exciting new development.

11. The BASROC research team and management structure

The BASROC research team is a multidisciplinary group of researchers working in particle physics, accelerator science, engineering, radiation oncology and clinical practice, and from a large number of highly-rated universities and research institutes, with good connections to industry and the NHS.

The project will have four programmes. Two major work packages will be: EMMA, to be constructed at the CCLRC Daresbury Laboratory, using the Energy Recovery Linac Prototype (ERLP) as an injector; and PAMELA, subsequently to be constructed in the new Richard Doll Building for Cancer Research on the University of Oxford's Old Road campus, using an 18 MeV cyclotron as an injector for which funds already exist. The third work package will be devoted to understanding the beam dynamics and developing the design codes for NS-FFAGs. The final work package will cover management of the project, including outreach, education, training, intellectual property management and relations with industry.

The project will be managed by BASROC, which was formed at a meeting in Wolfson College Oxford in February 2006. BASROC is in the process of concluding a formal agreement between the partners, including industry. Each of the three main workpackages will have its own team with a Project Leader and a Project Manager, reporting to a Project Board appointed by BASROC. A small international advisory committee will be created to provide independent advice and oversight for the project. The fourth workpackage will be the direct responsibility of the Project Board, with the specific tasks (outreach, training etc) contracted out to appropriate organisations, either within the BASROC consortium or to external suppliers if such expertise is not available.

There is already significant international interest in the EMMA and PAMELA proposals, and it is anticipated that there will be requests to join the project, with potentially significant resources, to enhance and accelerate the programme. A number of international partners have already submitted proposals to fund their participation in NS-FFAG related activities. It is important that BASROC is able to support projects from its own funds, in order to be able to manage the technology benefits, and to provide the best possible chance for UK industry to develop this exciting new technology, and for UK science and society to harvest the anticipated rewards.

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AUTHORS

1. Birmingham University Hospital

Professor Bleddyn Jones is Consultant in Clinical Oncology and Applied Radiobiology at University Hospital Birmingham, who is interested in mathematical modelling of radiation in cancer therapy including use of protons and ions.

2. CCLRC

Dr Rob Edgecock is the coordinator of international activities on NS-FFAGs, in particular EMMA and PAMELA.

Professor Mike Poole is the Director of ASTeC, the CCLRC Accelerator Science and Technology Centre. He has had a career in accelerator science and technology, working mainly on radiation sources and electron based facilities. He is also a leading member of the ERLP and 4GLS project teams, having been one of the originators of the energy recovery linac concept applied to a 4^{th} generation source.

3. Cockcroft Institute – Lancaster

Dr Rebecca Seviour has recently been appointed to a Lectureship in the Department of Engineering at Lancaster University. She is currently in charge of a major research thrust in RF cavity engineering and surface science within the Cockcroft Institute. Her past work has focused on resonant RF cavity engineering and parasitic multipactor discharges in RF systems. Dr Seviour will bring her RF engineering expertise to the BASROC consortium.

4. Cockcroft Institute – Liverpool

Dr Andy Wolski, a new faculty member in the Department of Physics at Liverpool, is a leading international accelerator scientist in the physics and engineering of electron accelerators whose interests are presently focused on the design and operation of "Damping Rings" for the International Linear Collider (ILC). He leads the international initiative (Global Design Effort) on the conceptual design which aims for completion at the end of 2006. He is building a major research group in the Cockcroft Institute with new staff and PhD students, in which his experience with electron machines will contribute much to the development of the feasibility of the FFAG approach to electron acceleration and delivery.

5. Cockcroft Institute – Manchester

Professor Roger Barlow leads the newly established and rapidly expanding Manchester University Cockcroft group. He has many years of international experience in accelerators, specialising in the study and simulation of the interactions of relativistic electrons with accelerator components.

6. Gray Cancer Institute

Professor Melvyn Folkard leads a Radiation Biophysics team at the Institute and has a strong interest in experimental methods for understanding the fundamental mechanisms of radiation damage. He has been central to the design and development of a range of novel systems for the exposure of cells, tissues, biological molecules and organisms using ionising and non-ionising radiations. Most notable, are the development of automated facilities for irradiating single cells and sub-cellular targets using micro-collimated and micro-focused radiations.

Professor Borivoj Vojnovic heads the Advanced Technology Development Group at the Gray Cancer Institute, with strong interests in the development and application of biomedical instrumentation systems. His background is in electronic engineering and radiation physics. The generation of ionising radiations and the development of associated systems to target and to image their effects are central to his group's activities. Specific interests include the construction and application of apparatus to study fast chemical and biological kinetic processes, using diverse techniques such as time-resolved fluorescence, pulse radiolysis, and a range of bio-imaging techniques. During his career, he has been involved with installations of electrostatic and radio-frequency accelerators and has contributed to the design of beam transport systems, dosimetry apparatus and machine control systems. More recently, his interests have shifted towards automation, design of software tools for high-throughput systems and the development of ultra-fast laser-based instrumentation, x-ray sources and similar devices, with specific applications to cancer and radiation research.

7. John Adams Institute - Oxford:

Professor Ken Peach, the Institute Director, has many years experience in experimental particle physics, and was Director of Particle Physics at CCLRC and Deputy Leader of the Experimental Physics Division at CERN. He was recently awarded the IOP Rutherford medal in part for playing "*played a key role in reviving accelerator science for particle physics applications in the UK*".

Dr John Cobb is Reader in Physics at the University of Oxford. Originally a particle physicist with experience of designing and operating hardware as well as data analysis, he is also working on the MICE muon cooling demonstration and has experience of both beam optics and electromagnetic design.

8. Glasgow University Beatson Oncology Centre

Professor Alex Elliott is Head of both the NHS (West of Scotland Health Boards) and University Departments of Clinical Physics. Primarily a nuclear medicine physicist, he has interests in targeted radionuclide therapy and cyclotrons (through positron emission tomography) and has experience of clinical usage of fast neutrons.

9. Imperial College Physics

Professor Kenneth Long has many years of experience in experimental particle physics and is spokesman of the UK Neutrino factory collaboration and the MICE-UK collaboration.

Dr Juergen Pozimski has many years of international experience in accelerator science and was involved in several main accelerator projects. His interests are novel acceleration and focusing structures, beam dynamics and diagnostics.

10. Leeds University Physics

Professor Bob Cywinski holds the Chair of Experimental Physics at Leeds University. He has three decades of experience in designing, building and utilizing international neutron and muon facilities, beam lines and instrumentation for the study of condensed matter in physics, materials, and the life and earth sciences. Currently he is a member of the international team working to secure approval for the European Spallation Source project.

11. Leeds University Hospitals

Professor David Thwaites leads the Radiotherapy Physics team in Leeds University Hospitals and has interests in radiation dosimetry and treatment planning, novel techniques in radiation oncology and mathematical modelling of radiation beams for clinical applications.

12. Oxford Radiation Oncology and Biology

Professor Gillies McKenna is Professor of Radiation Oncology and Biology at the University of Oxford and Director of the University of Oxford's new Initiative for Radiation Biology Research, which is jointly funded by Cancer Research UK, the Medical Research Council and the University of Oxford. The Initiative combines the Medical Research Council's Radiation and Genome Stability Unit and Cancer Research UK's Gray Cancer Institute.