Beams for European Neutrino Experiments

The Non-Scaling Fixed Field Alternating Gradient (NS-FFAG) accelerator
Part 2: Description of the proposed research and its context

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Abstract

The construction of a a non-scaling Fixed Field Alternating Gradient (NS-FFAG) accelerator is being proposed at Daresbury Laboratory. This ,is an unique and novel machine, of general interest and multiple application. It is also proposed to study a related accelerator for cancer therapy.
The use of FFAGs for acceleration of proton and muons for neutrino beams is one of the core subjects of BENE WP5b. BENE warmly supports this proposal and will contribute its expertise.

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Introduction

We propose to build a non-scaling Fixed Field Alternating Gradient (NS-FFAG) accelerator, a unique and novel machine, and to study a related accelerator for cancer therapy.

1 Background

Accelerator science has generally been associated with large-scale international facilities for particle and nuclear physics experiments. Recently electron, proton and heavy ion accelerators have developed increasingly important roles elsewhere in science, technology, and medicine, with applications ranging from treatment of cancers, radiopharmaceutical and medical isotope production, ion implantation, and secondary neutron and muon beams for studying the structure and dynamics of materials. This diversity of applications has demanding requirements to provide high beam power, high duty cycle and precisely controllable beams, at reasonable cost and with good reliability. FFAG rings offer a radical alternative to conventional accelerator technologies as they can deliver these requirements simultaneously. With fixed magnetic fields like a cyclotron and pulsed acceleration like a synchrotron they combine many of the positive features of both. In particular, FFAGs have:

- Fixed magnetic fields, enabling FFAGs to be cycled faster than synchrotrons, limited only by the rate of modulation of the RF, potentially up to 1 kHz [1]. This leads to simpler and cheaper power supplies and ease of operation compare with synchrotrons;
- Larger beam acceptance, allowing high intensities with low beam loss, so that operation and maintenance are easier, safer, and more cost-effective;
- A magnetic ring, like a synchrotron, allowing beam extraction at variable energies; FFAG rings can be chained to reach higher energies;
- Compact size, making them easier to locate in industrial and clinical environments.

FFAGs have the potential for a paradigm shift in accelerator technology, possibly replacing both cyclotrons and synchrotrons in existing applications, allowing development in new areas.

The FFAG was invented in the 1950's, in Japan, Russia and the US [2]. Three electron FFAGs were built at MURA [3] and successfully tested. As the emphasis at the time was for higher energy rather than better performance, synchrotrons with simpler magnets became the *de facto* standard accelerator technology. Later, proposals for FFAG based neutron spallation sources [4][5] were unsuccessful, due to the perceived complexity of the magnets.

More recently, FFAGs became the focus of renewed attention. In the proposed Neutrino Factory [6], the large acceptance and rapid acceleration rate of FFAGs would be ideal, because of the large emittance of the muon beam and the short lifetime of the muons. This led to the construction of two proton FFAGs, a 500 keV machine [7] in 2000 and a 150 MeV machine [8] in 2003 (see Figure 1). A 3-stage prototype of an accelerator-driven system for a sub-critical nuclear reactor [9] is currently being commissioned, a muon beam manipulation ring is under construction [10] and a number of machines for proton and carbon therapy, Boron Neutron Capture Therapy, CT-scanning and industrial irradiation are at various stages of prototyping and design [11].

The Japanese and MURA machines are scaling FFAGs, where the accelerated beam has geometrically similar orbits of increasing radius; the number of transverse oscillations per turn (the tune) remains fixed, and avoids the crossing of low-order resonances that give unstable operation [12]. In scaling FFAGs the RF frequency must be modulated to match the revolution period, and magnet apertures are large compared to a synchrotron. In addition, the magnetic field [13] follows the law $B \propto r^k$, (r is radius and the field index k is a large number, e.g. 7.5 for the machine in figure 1(b)). The magnets are complex and expensive to manufacture, and resonances can still be a problem [14]. The resulting cost and complexity may limit the use of scaling FFAGs in industry and medicine.

Figure 1: (a) The 500 keV (left) and (b) 150 MeV (right) proton scaling FFAGs built at the KEK laboratory in Japan

The NS-FFAG was invented in 1999 [15]. The magnetic design gives a parabolic variation of orbit length with energy [16], which can be arranged to greatly compress the range of orbit radii and thus the magnet aperture, while maintaining a linear magnetic field dependence. The small apertures and linear fields allow simplification and cost reduction compared with scaling machines. A further advantage is that for certain applications it is possible to use a fixed-frequency (and therefore simpler) RF system, allowing continuous operation like a cyclotron [16].

NS-FFAGs are unusual in that the magnet fields do not scale with energy: tunes will vary and many transverse resonance conditions will be crossed during acceleration, possibly leading to beam blow-up and loss. The fixed RF frequency also means that the bunch slips back and forth asynchronously during acceleration. This is a new acceleration mode not used or considered in standard accelerator design, *and no such machine has been built*. It is essential to build a proof-of-principle accelerator to demonstrate that it works, to study in detail their dynamic properties and to learn how to optimise the design for different applications. This is EMMA (Electron Model for Many Applications), whose construction is one of the main deliverables of this proposal. A design study is proposed for a FFAG for Charged Particle Therapy (CPT) called PAMELA (Particle Accelerator for MEdicaL Applications). As well as demonstrating the advantages of such machines for CPT, PAMELA will deliver a carbon ion beam for detailed studies in human cancer cell lines and murine cancers. The feasibility study and PAMELA design are deliverables of this proposal.

2 Programme and Methodology

There are three related work packages – EMMA, PAMELA and Applications. The EMMA work package will provide the basic tool to investigate NS-FFAGs. In parallel, the PAMELA design will proceed, to address the problems of tune variations and rapid RF modulation, and to deliver a prototype design for a real application. The initial operational experience of EMMA will be used to refine the PAMELA design. The Applications work package will explore opportunities for exploitation of this technology in other areas.

2.1 Work Package 1 - EMMA

As the primary purpose of EMMA is proving the principle of NS-FFAGs, it must have all the unique features of such accelerators, but with the flexibility to allow detailed studies. As a result, EMMA will require [17]: combined function magnets with linear magnetic fields to generate large variations in tune; independent variation of the dipole and

quadrupole components of these magnets to probe different regions of tune space during acceleration; fixed RF, to study asynchronous acceleration; ability to change this frequency by up to 1 part in 10^3 and the accelerating voltage over a factor of 6 to study the longitudinal dynamics; injecting beam at many energies, to study resonance crossing and some resonances in detail; and changing the position of individual magnets and magnetic field strengths to introduce errors of known size for resonance crossing studies.

Detailed simulation studies have been undertaken to identify the machine best able to meet these requirements. The selected accelerator is a 10-20MeV electron NS-FFAG using a doublet lattice and with 42 cells, each about 40cm long (see Figure 2), with RF cavities in every other cell, the cells in between being used for pumps and diagnostic equipment. The circumference is ~16.5m. The machine will be located at the Daresbury Laboratory and use the Energy Recovery Linac Prototype (ERLP) [18], currently under construction, as the injector. This is ideal for this purpose and can provide a beam with the required energy variability. Single bunches will be injected into EMMA, usually at 1Hz but with the possibility of going to 20Hz. There is sufficient space in the hall, and this will allow common use of some infrastructure for the two machines, bringing a considerable cost saving.

The design of EMMA is complete; the main elements are described in more detail below. The last section shows the results of simulation studies.

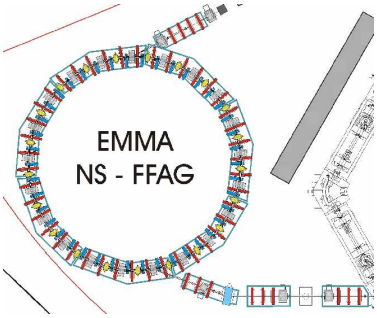

Figure 2: The EMMA ring at DL, showing the injection line on the right, the ring itself and the diagnostics line at the top. Part of the ERLP is shown on the far right.

Magnets: Although the EMMA F and D magnets are both combined function, their quadrupole component is much bigger than their dipole component. As a result, to permit these components to be varied independently, they are both quadrupoles and the dipole component is obtained by positioning them off-centre. Independent variability is achieved by varying the quadrupole strength and independently adjusting the magnet position. The magnets will be mounted on 7 girders, with 12 magnets on each. The mountings of all the magnets will be independently adjustable so that the required positional accuracy, 50μm, can be obtained using a laser alignment system designed for the ERLP. Further, the magnet position adjustment is accurate to better than 5μm [19]. As the inscribed radius of the quadrupole magnets (44mm for the F) is about the same as their thickness (55mm for the F), fringe fields will dominate the magnet performance. In addition, the magnets will be closely spaced and there will be an interaction between the fields. As a result, 3D finite element analysis is currently underway to check these effects.We are proceeding with advanced 3D design studies of two prototypes, one F and one D magnet, If these identify problems, small correction coils can be included in the design; this should not cause any difficulties. EMMA will need an injection line from the ERLP and an extraction, or diagnostics, line (see below) and these have been designed. The kicker magnets will need to switch off or on in about 20ns. Such magnets, with high speed thyratron switching, are routinely used in accelerators; whilst the 20ns switching time is demanding, similar performances are now achievable and significantly faster switching is being designed for future facilities.

RF system: The RF system is based on the existing 1.3GHz ELBE buncher cavities [20]. These simple cavities have had to be modified as the required beam aperture, 45mm, is bigger than that currently available, 25.4mm. Increasing the aperture has led to a reduction in the shunt impedance of the cavity, which would in turn bring an increase in the required power. As a result, the internal structure of the cavity has been re-optimised to restore the loss. The new aperture has brought a small increase in the external dimensions of the cavity. Each cavity is required to produce an accelerating voltage of between 20 and 120kV. The highest voltage will require 126kW of RF power and delivered from 7 IOTs [21].

Measurement	Device	Number	Resolution
Beam Position	4 button BPM	2/plane/cell in ring 4 in injection & Diagnostics lines	50μm
Beam Profile	OTR screens	3 in ring, 1 in injection and diagnostics lines	100μm pixels
Beam Current	Resistive wall monitor	4 RWMs 1 scope	2%
Phase	Resistive wall monitor	As above	10^o
Trans-Mission	Resistive wall monitor Faraday cup	As above 1	2%
Beam Loss	Beam Loss Monitor	4	2%
Mome-Ntum	BPMs and TOF from RWMs		100keV
Emitt-ance	Wire scanners	3 in diagnostics line	10%
Longit-udinal profile	Transverse deflecting cavity and screen	1 in diagnostics line	20keV 5^o

Table 1: Diagnostic devices required for EMMA.

Diagnostics: As EMMA is a test machine, the diagnostics are a crucial element of the project and must therefore be fully optimised. The requirements are summarised in Table 1. Note that some of the diagnostics will be in the ring itself, but any destructive measurements will be made in the diagnostics beamline. A beam extraction system has been designed that will allow the beam to be kicked into this line from any part of the aperture. In the ring, it is planned to have 2 button Beam Position Monitors (BPM) in each cell, with each BPM being read out on each turn for at least 5 turns. This will provide an accurate record of the beam orbits through the acceleration cycle. The BPMs can also be used to infer the beam momentum. There will be 3 Optical Transition Radiation detectors spread around the ring to measure the beam profile. Resistive Wall Monitors (RWM) are proposed to record the beam current on each turn and hence to measure the transmission through the ring. In addition, by using a sufficiently accurate oscilloscope, the RWMs will also be able to measure the beam phase with respect to the RF. Four beam loss monitors, similar to those of the ERLP, will be mounted around the ring, mainly for safety reasons. In the diagnostics beamline, there will be an emittance measurement system based on 3 wire scanners, and a longitudinal profile monitor in the diagnostics line, employing an ELBE kicking cavity to deflect the beam into a screen, in a similar way to that used at ELBE and SLAC [22]. In this way, the time dependence in the beam is converted into a position dependence on the screen. A Faraday cup in front of the beam dump will monitor the beam intensity run by run.

Other hardware: The remaining hardware components of EMMA (mechanical support structure, vacuum equipment, power distribution system, cooling system and control system) are all based on the equipment to be used for the ERLP.

Performance: The performance of EMMA has been studied using a variety of codes, in particular MADX and PTC [23] and two "home built" tracking codes, ZGOUBI [24] and an unnamed code developed in CCLRC [25]. These have been used to specify the hardware requirements for the machine and to demonstrate that it will deliver the performance specified above. In all cases, the codes give consistent results. Examples are shown in Figure 3 and Figure 4. Figure 3 shows the results of tracking studies in the ring, in particular, showing a large emittance beam accelerated from 10 to 20MeV and hence confirming that EMMA will work. Figure 4 shows the time of flight curves for four different lattices, showing a large variation, indicating that the machine can do a detailed study of longitudinal phase space. The inset shows the tune diagram, confirming that EMMA has the tune variation and can probe different regions of tune space.

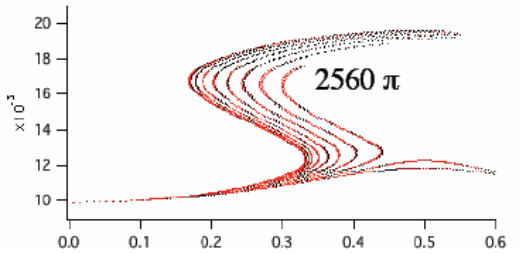

Figure 3: The longitudinal phase space in EMMA for single particles corresponding to a number of normalized emmittances. A beam up to 2560πm is accelerated to 20MeV.

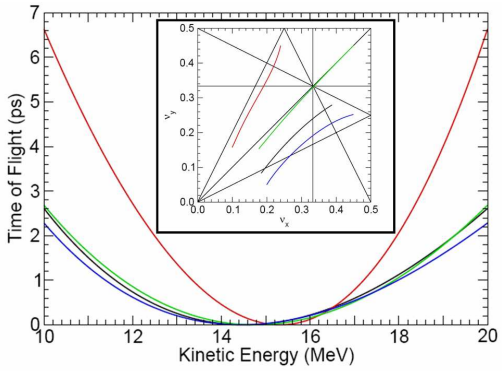

Figure 4: Time of flight curves for 4 different EMMA lattices, showing the almost parabolic shape characteristic of NS-FFAGs. The inset shows the tunes per cell for these lattices during acceleration.

Conclusion: EMMA is a vitally important project for the future of NS-FFAGs. It will show that they work and teach us much about how such machines will operate. The information it will provide will enable the design of NS-FFAGs for many applications and could initiate a revolution in future accelerator technology. Once the tests are complete, EMMA will be available as a teaching accelerator, enabling the next generation of accelerator scientists to undertake beam dynamics simulations and then try them out on a unique facility. Further information about the EMMA project will be found on http://basroc.ac.uk/EMMA.htm

2.2 Work Package 2 - PAMELA

About a third of the world's 15000 accelerators are used for cancer therapy and other medical applications. The characteristics of FFAGs make them ideally suited to such applications, and their impact will therefore be considerable. Indeed there is already growing interest in the use of scaling FFAGs for particle therapy, with several projects at various stages of development [26]. FFAGs offer a unique combination of desirable characteristics, namely high beam intensity, minimising the duration of treatment and able to produce highly collimated beams with sufficient intensity for spot-scanning; high repetition rate, important for spot-scanning and running in respiration-gated mode [27]; ability to accelerate carbon ions as well as protons to therapy energies; real-time variable energy in IGRT; beam extraction into more than one beam line; small beam losses, reducing activation and helping minimise the uncertainties in delivered dose; easy operation and maintenance, ideal in a clinical environment.

NS-FFAGs are well suited for Charged Particle Therapy (CPT), as the smaller magnet size and greater compactness offers considerable cost and operational benefits, such as the ease of delivering a beam at any energy. Whilst EMMA will facilitate the development and testing of generic NS-FFAG technology, the PAMELA work package will, in parallel, focus on those specific machine parameters demanded by therapy applications. The intrinsic cross fertilisation between EMMA and PAMELA will ensure that a functional design of a particle therapy NS-FFAG will be delivered on the shortest possible timescale. Indeed, negotiations are already underway to secure funding to construct PAMELA, based on the delivered design, probably on the Churchill Hospital site (Oxford).

Some initial simulation work on the use of NS-FFAGs for CPT has been done, for example by a small collaboration led by Brookhaven National Laboratory [28]. This envisages a proton and carbon ion complex consisting of an RFQ and short linac, and three rings. Both proton and carbon ions are accelerated in the linac. Protons are accelerated to 31 and 250MeV in the first two rings and carbon to 69 and 400MeV/u in the second and third. The rings are 35, 43 and 52m in circumference and the largest horizontal magnet aperture, in the third ring, is less than 40mm. These studies have been useful in identifying potential technical difficulties. For example, as the magnets are essentially linear, there will be many resonance crossings. While a novel acceleration technique, using jumps in harmonic number, could be used to have a faster acceleration rate than a synchrotron, the resonances may have too severe an effect on the beam. EMMA will confirm whether this is a viable option. If it is, considerable additional work will be needed for a full design, as well detailed studies of the RF system and magnets.

Several alternatives to the Brookhaven model are under consideration. One is the "semi-scaling" FFAG in which the tune variations in the accelerators are minimised using non-linear magnets. This route requires far more detailed investigation, particularly as early studies based on sextupoles highlighted problems with dynamic aperture. Two other approaches appear promising [29],[30], but neither is yet sufficiently advanced to allow conclusions to be drawn.

Whilst it is clear that NS-FFAGs have a huge potential for particle therapy, it is also clear that this is some way from being fully realised. Under the PAMELA work package, we propose to employ three accelerator physicists, at least one senior and with relevant experience, to undertake a detailed study of the most promising option, a therapy complex based on semi-scaling type FFAGs. As BASROC has close links with all those already working in this area, this will be supported by a wider collaboration. We shall contribute to the on-going work whilst investigating alternative solutions.

The first stage of this work will be the design of a machine to deliver a 450MeV/u carbon ion beam with small or zero tune variations, including detailed lattice and tracking studies. The second stage will use existing expertise in the consortium to undertake a design of the magnets and RF system for this machine. The output from these stages will be a demonstration of feasibility. The third stage will be a preliminary cost estimate for the complex, allowing comparison with existing technologies on both performance and cost.

The resulting design will then be scaled to a 230MeV proton prototype, with cost estimate. This machine will be suitable

for proton therapy studies and could also produce 68 MeV/u carbon ions. This is particularly important as it will offer the opportunity of testing whether carbon ion therapy is indeed more effective than standard radiotherapy in a clinical environment. Alternatively, if this is too expensive, scaling to 70Mev would provide a lower performance but still viable NS-FFAG prototype, able to carry out more limited comparisons between hadron and radiotherapy.

The implications of PAMELA for hadron therapy are far reaching: Radiotherapy remains second only to surgery in its efficacy as a treatment for cancer and recent advances in charged particle therapy offer significant improvements in terms of patient outcomes and quality of life. The development of EMMA will enable a route to the compact, versatile machines needed to deliver charged particle beams in the future and provide the necessary training opportunities to enable those involved to gain the necessary experience and skills to operate this new generation of equipment effectively; the prototype for such machines is PAMELA.

Single-hit ion microbeams have been developed to study radiobiological effects in cultured cells at low doses (i.e. where only a few cells in a population are traversed by an ion). These studies reveal effects that could have profound impacts on clinical treatment. For example, it is evident that unirradiated cells can also be damaged when an irradiated cell is nearby. If these "bystander effects" occur *in vivo*, then they will affect the amount of damage in the low-dose region around the targeted volume. Furthermore, the cell-to-cell signalling that underpins these effects could provide an exploitable pathway to improve the efficacy of ion radiotherapy. To date, these studies have mostly made use of low-energy light ions and cultured cells. The next key step is to explore these effects using a range of penetrating ions in tissue models. PAMELA offers unique opportunities, with its flexible ion species and energy. Moreover, the technology developed for PAMELA can itself, be used as a springboard to develop the next generation of charged particle therapy (CPT) machines, effectively leading the rest of the world by developing a compact, versatile machine for CPT.

Conclusion: PAMELA offers a unique set of opportunities to develop CPT because of its flexibility in ion species and energy. The technology developed for PAMELA will be a springboard to develop the next generation of machines for CPT, giving the UK a potential world lead in compact, versatile, easily operated machines for a clinical environment.

2.3 Work Package 3 - Applications

The last work package focuses upon the exploitation of FFAG technology in a wider context than just medical applications. It is essential that other applications are considered in the early stages, as each application places specific demands on beam energy and size, repetition rate, pulse width, emittance, extraction etc, which must be fed back into the design. The work package will identify the most appropriate applications for FFAGs and the machine parameters needed to ensure the widest possible application of this emerging technology and hence the widest possible market for the resulting components. Specific applications considered as part of this work package are discussed below.

2.3.1 Fundamental research (PPARC, CCLRC)

The Neutrino Factory is the subject of a major international study, aiming to make intense neutrino beams from the decay of muons stored in a ring. 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. FFAG accelerators with their rapid cycling time, could be used in the proton driver and the muon accelerator. They are more cost effective than linear accelerators for the high energy, high power part of the proton driver delivering beam on the target, and could have lower thermal shock in the target than a synchrotron. A critical design issue is the short muon lifetime and therefore the rapid acceleration, and the large beam size and broad energy spread to be captured within the acceptance of the accelerator. Until recently, costly recirculating linear accelerators were thought to be the only solution. An NS-FFAG would provide a technically superior and cost-effective way to capture and accelerate the muons.

NS-FFAGs are being considered for intensity upgrades to existing proton accelerator chains used for fundamental research. In particular, a new booster ring for the AGS at Brookhaven has been designed, and FFAGs are an option for future developments at CERN. Electron FFAGs are being considered for two applications, though work is at an early stage. A 10GeV NS-FFAG is being studied to produce e-p and e-Au collisions with RHIC at Brookhaven. An 8GeV electron machine is being investigated as a light source.

2.3.2 Charged Particle Therapy (MRC, EPSRC, PPARC)

We are continuously exposed to ionizing radiation (charged particles and photons). Despite this, surprisingly little is known about the harm that arises from our day-to-day exposure to background radiation, which can vary greatly with location and occupation. At the same time, deliberate exposure to ionizing radiation (i.e. radiotherapy) remains second only to surgery in its efficacy as a treatment for cancer and recent advances in charged particle therapy offer significant improvements in patient outcomes and quality of life.

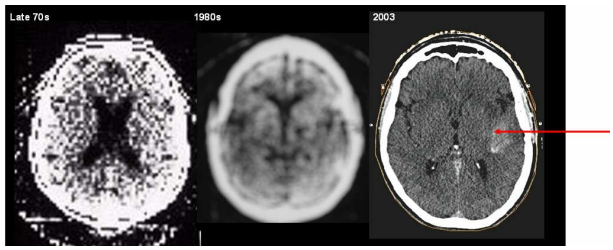

Figure 5: Advances in brain imaging mean that small tumours can now be identified. The arrow is pointing to a glioblastoma which is now clearly visible on the most modern CT brain scan.

Clinical applications of Charged Particle Beams

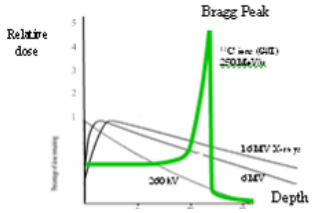

Figure 6: 2 Depth distribution and energy deposition of different energies of x-rays compared to C ions

Since the early 1970's, huge advances in medical imaging have allowed cancers that were previously undetected to be accurately identified and treated (see Figure 5). To treat these very small tumours new treatment strategies must be devised. Particle therapy using protons and light ions are a promising development in radiotherapy [31]. Conventional radiotherapy uses high energy photons (x-rays). Compared with these, protons and light ions produce excellent dose distributions to tumours and reduced doses to normal tissues. Improved treatments, with a marked (over 50%) total energy deposition in the tumour, reduced dose in healthy tissue providing better prospects of reduced severe side effects and improved quality of life for the patient. Like x-rays, protons and light ions cause DNA damage but deposit their energy more selectively (see Figure 6). As the particles pass through tissue, they lose energy through inelastic scattering and finally come to rest (at the Bragg peak) through electronic and nuclear interac-

tions. Thus, with light ions, most of the energy deposition occurs in the vicinity of Bragg peak with almost none a short distance beyond. By positioning many Bragg peaks within a cancer, it is possible to increase the tumour dose while decreasing the dose to the surrounding healthy tissue. As there is a minimal exit dose, structures beyond the Bragg peak are largely un-irradiated.

As mentioned earlier, after surgery the most effective cure for cancer is radiotherapy, although these two modalities are often combined. The advantages of particle radiotherapy over x-rays can be summarised as: lower dose to healthy tissues surrounding the tumour; no exit dose so that vital organs (e.g heart and lung in breast cancer, optic nerve in brain tumours and spinal column in tumours of the head and neck, rectum in the pelvis) can be spared; reduced beam scattering penumbra meaning small volumes can be targetted accurately keeping up with the latest advances in imaging resolution; children are a special case: the risk of radiation induced malignancy, based on standard radiation protection data, is predicted to reduce by 10-15 fold in some instances using protons.

From Bench to Bedside

To capitalise on the advantages that light ions offer to patients and to understand the risks associated with environmental exposure to radiation, there needs to be a detailed understanding of the mechanisms by which light ions interact with living cells and tissue. An important technique for such studies is single-hit ion micro- or nano-beams. Sub-cellular targeting using single ions makes it possible to study the response of cells to precisely controlled radiation doses at specific parts of their structure and at specific points in the cell cycle (Figure 7). These can then be compared with the predicted cell response from transfected mosaic spheroid models. Precise control over the particle energy makes it possible to irradiate cells at the Bragg peak, at the track-end as the particle comes to rest and the most effective part to kill the tumour cells. Such studies will inform the design of PAMELA. In order to translate the results of cellular irradiation into the clinical environment unambiguously, studies in tissue are also needed. These require high energy beams of light ions such as those of PAMELA.

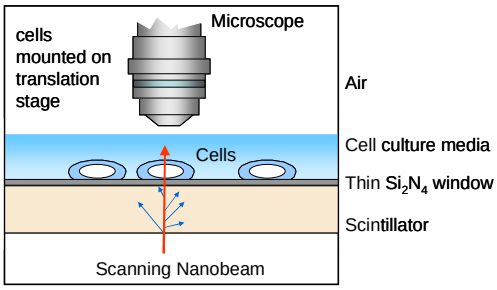

Figure 7*: Schematic of cell irradiation*

2.3.3 Materials research (EPSRC, CCLRC, NERC, BBSRC)

Neutrons play a definitive role in our understanding of the material world, enabling clear insights into the structures and dynamics of materials across all disciplines, and facilitating the development of new and exciting materials for science, technology and medicine. A proton NS-FFAG could generate spallation neutrons, on a large scale for neutron scattering science, or on a smaller scales for entirely novel dedicated neutron radiography, tomography or irradiation facilities. Such miniature neutron sources may provide a new generation of dedicated boron neutron capture facilities for clinical application, radiopharmaceutical production, sterilisation, and element specific gamma ray analysis and imaging of composite objects in an industrial environment. Notably, the Technology Panel of the recent ministerial review of the UK neutron strategy identified FFAGs as one of a range of technologies that the UK should develop.

FFAG proton beams can generate intense secondary low energy muons beams to study material properties using muon spin rotation and relaxation and to explore the limits of the Standard Model in fundamental physics. Rapid cycling FFAGs offer the opportunity of developing the world's first dedicated muon sources, with beam intensities orders of magnitude higher than those currently available.

Industrial and engineering applications using primary accelerated charged particle beams include testing fully packaged electronic devices for spacecraft applications by emulating the effects that the devices experience in space and allowing the effects of the solar wind on the packaged devices to be studied without removing the packaging. Extended the energy ranges allow time of flight elastic recoil detection analysis to be undertaken. This technique, which allows elemental areal and depth profiles to be determined, is particularly useful for light atoms and in semiconductors it will enable hydrogen and helium profiles in technologically important materials to be determined. There are also applications in real catalysts as the energies available will permit implantation into catalytic pellets that can then be subjected to real process conditions. One of the main criticisms of research in catalysis is that the effects observed are difficult to translate in to real process situations. By using higher energies available it will be possible to prepare materials that can be transferred directly into real process systems. In semiconductors it will enable hydrogen and helium profiles in technologically important materials such as SMARTCUT to be determined. It will be possible to develop and test these applications directly with PAMELA.

2.3.4 Environment and energy generation (NERC, EPSRC)

Environmental change and long term prospects for non-renewable fuels are causing the UK and other governments to rethink clean energy strategies. It appears that a reconsideration of nuclear power, despite its attendant risks and public suspicion, is inevitable. A novel but viable approach to nuclear power for electricity generation is to use a sub-critical accelerator-driven thorium reactor. As the accelerator must be operational to produce power, there is an inherent safety advantage over conventional critical nuclear fission reactors. The key issues for the proton accelerator in such applications are high reliability, ease of operation and available average beam power. FFAG accelerators could offer all these advantages at lower cost than linear accelerators. In addition FFAG technology could well impact related energy issues, such as the accelerator-driven burning of long-lived radioactive waste by transmutation, as being currently studied in Europe (EUROTRANS Project) with conventional Linacs.

2.3.5 Novel industrial applications

For example, there is potential for a proton/deuteron FFAG to be used for neutron generation. Fast neutrons so produced have a high cross-section for interaction with low atomic number elements such as nitrogen that are found in high concentrations in explosive materials. Following the neutron interaction, high energy gamma-rays are produced whose energies are element specific. These high energy gamma rays are able to escape even quite large objects, hence such a technique is well suited to high sensitivity explosives detection in ISO containers and other large objects.

Conclusion: FFAGs have great relevance to science, technology and medicine and could revolutionise accelerator driven science across many disciplines. However FFAG design and operational parameters will depend crucially upon specific application. Consideration of such applications is thus essential throughout the development programme to

inform the design process and to set machine characteristics. The Applications Work Package will oversee this process.

3 Relevance to Beneficiaries

There are currently of the order of 15000 accelerators world wide. These serve almost all aspects of scientific, technical, medical and even artistic endeavour. FFAG development will impact and benefit each of these areas. More precisely there are four groups of beneficiaries. Accelerator scientists will benefit through the design, construction, operation and understanding of a new type of accelerator suitable for a wide range of special applications. Frontier sciences, such as particle physics (e.g. Neutrino Factory) and other fundamental sciences (e.g. through improved spallation neutron sources), will benefit from the development of more cost-effective high power accelerators using the special features of the NS-FFAG. Medical science will benefit from new, more compact, less complex and more flexible proton and ion source for cancer therapy and basic research. Industry will benefit through the development of new applications for, and extensions of, their existing technologies and expertise in advanced magnet technology and RF. The structure of BASROC (see below) ensures that all relevant expertise is available within the consortium.

4 Dissemination and Exploitation

The scientific and technical results of this and associated research will be disseminated through conference presentations (as usual for accelerator R&D), journal publications where appropriate, seminars and public events organised through the collaborating institutions and through the BASROC website (http://basroc.rl.ac.uk/). Patents will be sought for commercially exploitable developments. A project of this nature, particularly with its emphasis on clinical applications, is of considerable public interest: we have therefore budgeted for a public understanding of science component to deliver a professionally produced documentary on FFAG applications in science and medicine. Articles describing the work proposed here have already appeared in *Physics World*, *Frontiers*, and the *CERN Courier*.

Effective commercial exploitation of new technology cannot be achieved by simply handing over completed designs to industry at the end the research and development programme. It is vital that relevant industrial organisations are engaged in the project from the outset as this will allow them to input valuable information on the manufacturability of the final product and give them a sense of 'ownership' in the project. Without this input, design decisions could be made which will increase the production costs and render the final design uneconomic to produce, resulting in a non-optimum return on investment for the research.

BASROC recognises the need for the UK to become a knowledge economy and exploitation of the technology, knowledge and know-how developed is a key part of this proposal. Through the High Power RF Faraday Partnership, UK based industry whose business encompasses the design, building and maintenance of medical and scientific accelerators, their components and sub-systems have been engaged from the formation of the consortium. This is evidenced through the industrial representation on the BASROC Board and the Associates Committee. These Associates will have full visibility of the programme and will be able to input their comments and suggestions to influence the technical direction of the programme at regular meetings.

A primary objective of the proposal is to develop, design and demonstrate an affordable Non-Scaling Fixed Field Alternating Gradient accelerator. To achieve this, the proposal includes the manufacturing of demonstration hardware. The Procurement Policy of the Consortium will ensure best value is obtained consistent with the strategic objective of commercial exploitation of the technology.

By the end of the project, the UK will have demonstrated its ability to design, build and test a NS-FFAG accelerator, with the close engagement of UK industry throughout the project. It is conceivable that additional knowledge transfer will be needed following the successful completion of the project. If this is the case then the need will be identified and other mechanisms (eg Knowledge Transfer Partnerships, collaborative R & D grants, etc) will be used to complete fill the gaps.

5 Other issues

BASROC, a collaboration of particle and accelerator scientists, radiation oncologists and industry, was formed in February 2006 to promote UK involvement in the development of advanced accelerators for science, medicine and industry. The consortium structure is shown in Figure 8.

The *Associates Committee*, one member for each organisation signing the Consortium Agreement, appoints, and can remove, the BASROC Board. The *BASROC Board* has a Chairman, Secretary and up to five others, at least one each from industry and CCLRC, at least two from HEI's, with at least one having a medical background. The *Advisory Committee* of up to five internationally recognised experts in the field is appointed by the Board. The Project Leader (PI) and Project Manager shall be appointed by, and report to, the Board. A *Project Management Committee* will be created for each project sponsored by BASROC. The Board will create a Project Management Committee, chaired by a member of the Board acting as Project Sponsor, consisting of the Project Leader and Project Manager, one other member nominated by the Board and one nominated by the Associates Committee. The Work Package leaders are appointed by the Board on the advice of the Project Leader and the Project Manager. The main positions in the Project Team are shown in Figure 9.

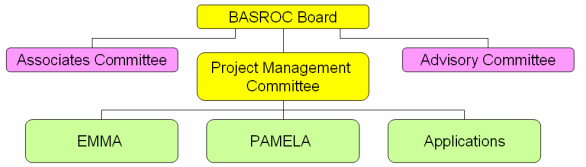

Figure 8: The structure of BASROC and the Project Management

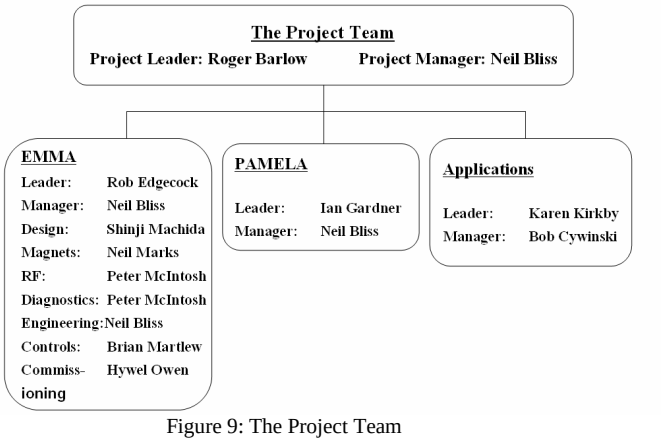

Figure 9: The Project Team

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