

The rise of the FFAG

Projects based on FFAG accelerators are beginning to flourish throughout the world.

The concept of fixed-field alternating-gradient (FFAG) accelerators was put forward in the early 1950s, as a possible way of applying the methods of strong focusing and phase stability to particle acceleration. An FFAG ring is a circular assembly of fixed-field magnets that strongly focus the accelerated beam, similar to that in an alternating-gradient synchrotron. However, as the magnetic field remains constant by definition, the beam spirals radially during the acceleration process, as in a cyclotron. Consequently, FFAGs feature magnets with a large transverse aperture and therefore high-beam acceptances in both momentum and space. Fast acceleration, high repetition rate and a large 6-D acceptance are the potential benefits of FFAGs that triggered their rebirth at the end of the 1990s, mainly in Japan (*CERN Courier* July/August 2004 p23). Since then the concept has been revisited in depth and this has led to a dual machine classification: scaling (invariant-focusing) FFAGs and non-scaling FFAGs.

In scaling FFAGs, the orbit shape and the optics of the beam are kept unchanged during the acceleration by applying a non-linear magnetic field of the form $B = B_0 (r/r_0)^k$, where k is the field index. Scaling FFAGs may be seen as an evolution of the synchrocyclotron concept, but offering more flexibility and potentially better performance in various application domains. The Japanese have recently constructed prototypes of radial-sector proton rings following this concept. They showed that modern 3D computer-aided methods allow accurate and reliable design of the sophisticated non-linear FFAG magnets. They also led to the development of a broadband and high-gradient RF cavity technology that makes fast acceleration and high repetition rates possible.

In non-scaling FFAGs, on the other hand, the betatron tunes are allowed to vary during the acceleration process. This freedom opens up new concepts that have been investigated with the help of modern particle-tracking computing techniques. Under the hypothesis that the total acceleration time is kept sufficiently short, the fast crossing of betatron resonances should have little effect on the beam stability. This new regime is sometimes referred to as "curved linear acceleration", meaning that there is no cyclic component in the beam motion equations. Non-scaling FFAGs tend to have much smaller transverse apertures than scaling machines.

FFAGs in Japan

The world's first proton FFAG accelerator, the Proof-of-Principle FFAG (POP-FFAG) was built at KEK in Japan in 2000 (*CERN Courier* October 2000 p11). At approximately the same time, researchers recognized that FFAG accelerators can feature rapid acceleration with large momentum acceptance. These are exactly the properties required for muon acceleration, for the production of medical



Fig. 1. The proton FFAG accelerator developed at Kyoto University Research Reactor Institute (KURRI), Japan, for a basic experiment on accelerator-driven systems. A third injector ring is located outside this image frame. (Courtesy KURRI.)

proton beams and for accelerator-driven systems (ADS) for nuclear energy. To investigate this potential, a team at KEK developed the first prototype of a large-scale proton FFAG accelerator. In 2004, it successfully accelerated a proton beam up to 150 MeV with a repetition rate of 100 Hz. Since then, intensive studies and discussions have taken place and various novel ideas have emerged that have led ultimately to new application projects for FFAG accelerators at several institutes in Japan.

A team at the University of Kyoto has developed a proton FFAG accelerator for basic research on ADS experiments. Here, the beam is delivered to the existing critical assembly of the Kyoto University Research Reactor Institute (KURRI). The whole machine is a cascade of three FFAG rings (figure 1). The beam was recently successfully accelerated up to 100 MeV and the first ADS experiment is due to start this summer.

Medical applications of FFAG accelerators have also been proposed in two different fields: hadron therapy and boron neutron-capture therapy (BNCT). For BNCT, an accelerator-based intense thermal or epithermal neutron source has been developed at KURRI, using an FFAG storage ring with a thin internal beryllium target (figure 2, p22). The growth of the beam emittance and the energy distortion caused by scattering in the target can be controlled using ionization cooling, a functionality that could not be used in a cyclotron owing to the lack of space. After completion of the whole system, recently the beam was successfully accumulated in the ring and neutron production has already been observed. This constitutes the first experimental demonstration of the efficiency of ionization cooling.

At the University of Osaka there is a proposal to build a highly intense muon source using the 50 GeV proton beam of the synchrotron at the Japan Proton Accelerator Research Complex. In the project, called PRISM, longitudinal phase-space rotation to narrow the initial energy spread of a muon beam by a scaling FFAG >

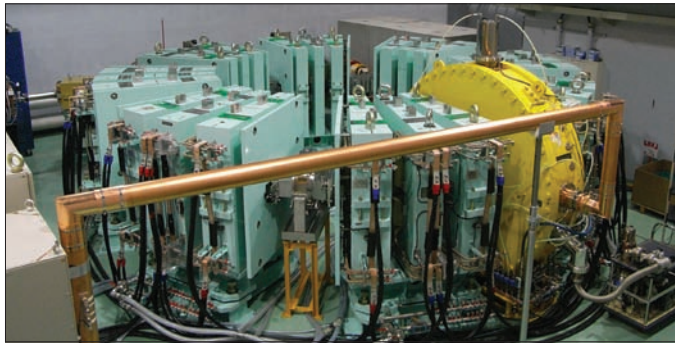


Fig. 2. The neutron source for boron neutron-capture therapy at KURRI uses an FFAG storage ring with an internal target. (Courtesy Y Mori.)

ring – featuring a large energy acceptance – has been developed to search for lepton-flavour violation in muon interactions. The ring consists of 10 magnets and 5 magnetic alloy RF cavities with a frequency and a gradient of 5 MHz and 200 kV/m, respectively.

The University of Kyusyu also has a new accelerator facility under construction. The main machine will be a 150 MeV proton FFAG accelerator whose design closely follows the one at KEK described above. This will be available for various applications, such as nuclear physics and material science.

EMMA in the UK

In the UK, non-scaling FFAGs are currently being studied for a variety of applications, including hadron therapy, ADS and the rapid acceleration of muons for a neutrino factory and a muon collider. The unique features of such machines mean that detailed development for these applications requires the construction of a proof-of-principle accelerator to explore in detail the beam dynamics to gain experience in the design and construction of non-scaling FFAGs, and to benchmark the computer codes employed in the studies.

This new machine, the Electron Model for Many Applications (EMMA) will be built at the Daresbury Laboratory of the Science and Technology Facilities Council (STFC). EMMA has been funded as part of the British Accelerator Science and Radiation Oncology Consortium (BASROC), which has also funded the design of a non-scaling FFAG, PAMELA, for the acceleration of carbon ions and protons for hadron therapy, and for studies of other potential applications of this technology.

EMMA will be a 10–20 MeV electron linear, non-scaling FFAG, designed with the necessary flexibility to allow the detailed studies required. In addition, it will use the linac for the Accelerators and Lasers In Combined Experiments (ALICE) project as an injector (figure 3). ALICE can deliver beams at any energy between 10 and 20 MeV, an important requirement for a complete study of resonance crossings in EMMA.

EMMA will use a doublet lattice and the ring will consist of 42 cells, each about 40 cm long. There will be 1.3 GHz RF cavities in every other cell, except around the injection and extraction regions. The intermediate cells will be used for diagnostics and pumps. The experimental nature of the accelerator means that it is important to have sufficient diagnostic devices. Within the EMMA ring, there will be two beam-position monitors in each cell, two wire scanners, two motorized screens and a wall current monitor. A beam-loss monitor, segmented into four sections, will surround the ring. A number of measurements can be

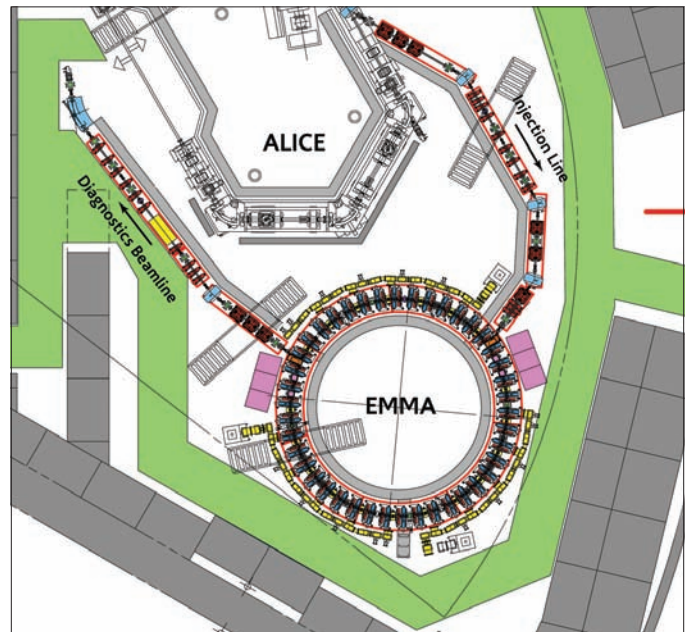


Fig. 3. The layout for EMMA, the non-scaling FFAG proof-of-principle project to be built at Daresbury in the UK. (Courtesy STFC.)

made only outside the ring and hence an extraction line has been designed to include emittance, longitudinal beam profile and momentum measurements. There will also be instruments in the injection line to measure the beam properties on entrance to EMMA.

The designs of the ring and the injection and extraction lines are now complete, and detailed engineering studies are far advanced. Prototypes for some major systems have already been built and tested, and construction of the others will take place this year. Construction of the machine itself should be finished towards the end of 2009.

RACCAM in France

Scaling spiral-sector FFAGs are now seen as good candidates for hadron therapy applications, with various potential advantages, such as variable extracted energy and high repetition rates compared with cyclotrons, and simplicity of operation when compared with synchrotrons. These considerations have motivated the R&D project Recherche en Accélérateurs et Applications Médicales (RACCAM), which is based at the Laboratoire de Physique Subatomique et de Cosmologie (LPSC) in Grenoble and has received a grant for 2006–2008 from the French National Research Agency. The RACCAM project aims to produce a preliminary design study of a variable-energy proton installation, based on a 5–15 MeV⁺ injector cyclotron followed by a spiral-lattice FFAG ring with an extraction energy of 70–180 MeV. This study is now close to completion. The project also includes the prototyping of a spiral magnet capable of delivering the required r^h field. A magnet of this type is now under construction at SIGMAPHI in France (figure 4).

RACCAM began in 2005 as a collaboration between LPSC, the radiotherapy department at the Grenoble University Hospital, and the magnet constructor SIGMAPHI. The collaboration has since rapidly expanded to include two more companies, IBA and AIMA, and the Antoine Lacassagne proton therapy clinic in Nice. Preliminary studies have led to a prototype proton therapy accelerator project, which could be hosted by the Antoine Lacassagne proton-therapy

clinic (see cover). RACCAM has organized several international-scale meetings, including the FFAG 2007 workshop in Grenoble, and the Fixed-Field Synchrotrons and Hadrontherapy workshop, the first of the kind, in Nice in November 2007.

The international accelerator community is rapidly gaining knowledge of FFAGs and of their rich potential in several key applications. More than four large-scale prototypes are presently either under construction or commissioning in JAPAN and in the UK. There is no doubt that we are now getting close to the first real use of FFAGs for physics research or medicine.

Further reading

All details concerning the RACCAM collaboration can be found at: http://lpsc.in2p3.fr/service_accelerateurs/raccam.htm. For more about BASROC, see <http://basroc.rl.ac.uk>.

Résumé

L'essor des FFAG

Le concept des accélérateurs à gradients alternés et à champ fixe (FFAG) a été proposé au début des années 50 dans l'idée d'appliquer les méthodes de la focalisation forte et de la stabilité de phase à l'accélération des particules. Ces machines permettent une accélération rapide, une fréquence de répétition élevée et une grande acceptation en impulsion et en espace. Ces avantages potentiels ont motivé la renaissance des FFAG dans les

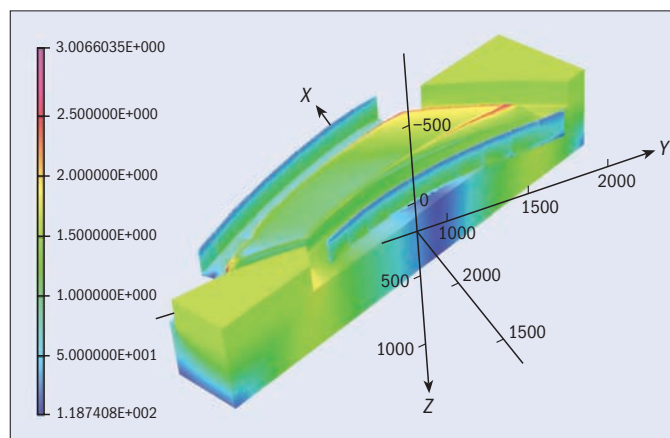


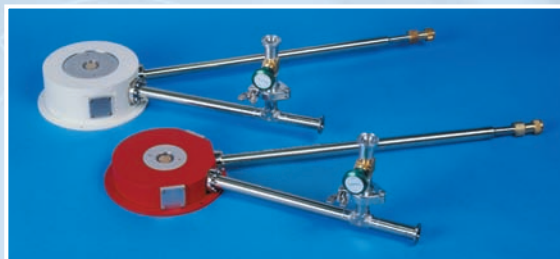
Fig 4. A prototype spiral dipole for the RACCAM project in France, which can deliver the field for a scaling FFAG. (Courtesy SIGMAPHI Vannes.)

années 90, essentiellement au Japon. Depuis, la communauté internationale des accélérateurs apprend à les connaître et découvre leur important potentiel pour plusieurs applications clés. Plus de quatre grands prototypes sont en cours de construction ou de mise en service au Japon et au Royaume-Uni.

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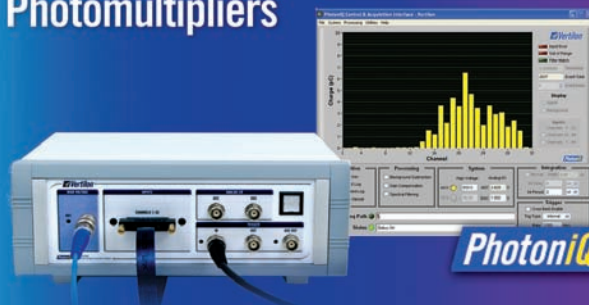


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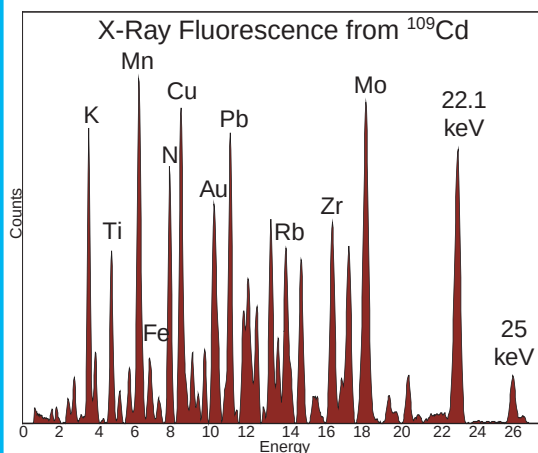
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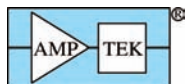
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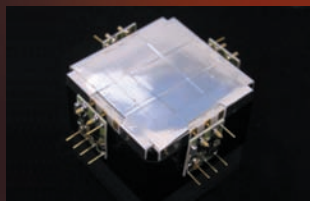
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