Fixed Field Alternating Gradient Accelerators - overview, status

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Abstract

INTRODUCTION

Being operated with fixed field magnets, and liable to house large accelerating gradients, FFAGs are by essence fast cycling accelerators [1], by contrast with pulsed synchrotron limited to about 50 Hz by magnet ramping. In addition, they feature very large geometrical and momentum acceptance, which make them propitious to the handling of short-lived, or large emittance, or highly charged beams.

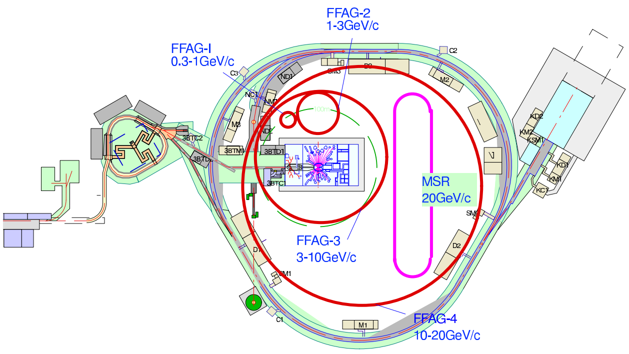

Figure 1: Neutrino factory scheme at J-PARC, using a cascade of 4 *scaling* muon FFAG rings.

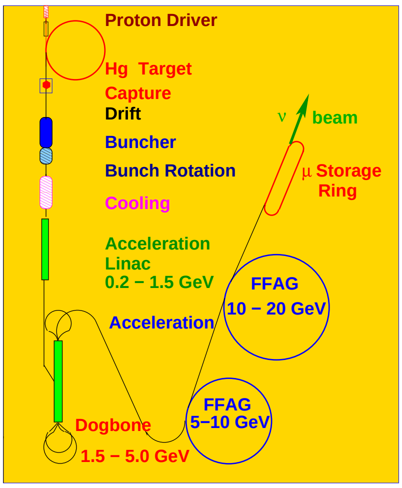

Figure 2: Baseline neutrino factory scheme with two *linear* muon FFAGs in series.

For that reason for instance, they appear as a preferred mean for the capture and/or acceleration of muon beams in the Neutrino Factory (Figs. 1, 2) [2].

Fast acceleration of ultra-relativistic muon beams (v/c∼1 regime), together with more general considerations proper to linear optics FFAGs, as the issues of resonance crossing, non-invariant focusing, have motivated the construction of an electron model of a muon accelerator based on linear optics at Daresbury, over the 2007-2010 period, see below.

Rapid acceleration and large acceptance also make the interest of FFAGs in the v/c<1 regime, where beam manipulation methods are that of synchrotrons : longitudinal phase stability, strong focusing, variable energy, multi- or single-turn injection, high efficiency fast or resonant extraction, etc. For these reasons they have been subject to extensive R&D since the late 1990s in Japan, where several proton machines have been built and successfully operated, see below.

Other prospects of FFAG applications include hadrontherapy, see below, as well as proton drivers possibly based on variants of the FFAG optics (see Ref. [3] for instance). The reader is referred to the recent FFAG workshops [4], 17 over the 1999-2008 period, for more information.

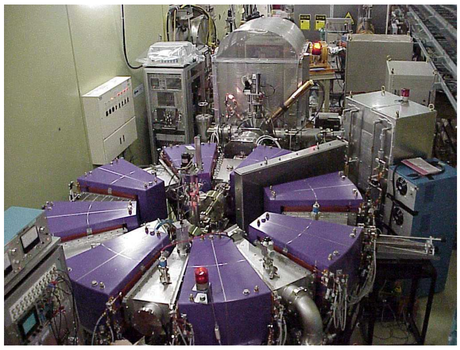

Figure 3: The POP FFAG.

Figure 4: KEK 150 MeV FFAG.

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FFAG R&D IN JAPAN

The world's first proton FFAG accelerator (POP-FFAG, Fig. 3) was built in Japan - at KEK - in 2000. At approximately the same time, it was recognized that FFAG accelerators may feature rapid acceleration with large momentum acceptance, exactly the properties required for both muon acceleration and production of proton beams for medical applications or for ADS (Accelerator Driven Systems for nuclear energy).

To investigate this potential, a prototype of large scale proton FFAG accelerator was developed at KEK (Fig. 4). 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 which ultimately have led to new FFAG accelerator application projects at several institutes in Japan.

ADS-REACTOR

In the University of Kyoto, a proton FFAG accelerator has been developed for basic research work on ADS (Accelerator Driven System for nuclear energy) experiments. Here, the beam is delivered to the existing critical assembly (KUCA) of the Kyoto University Research Reactor Institute (KURRI). The whole machine is a cascade of three FFAG rings, Figs. 5, 6. The beam has recently been accelerated up to 100 MeV, machine commissioning is now underway in view of first ADS experiments.

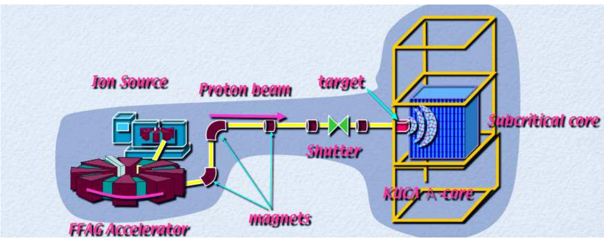

Figure 5: A scheme of the KURR-Institute ADS assembly, ~100 W core on the right, FFAG accelerator assembly on the left hand side.

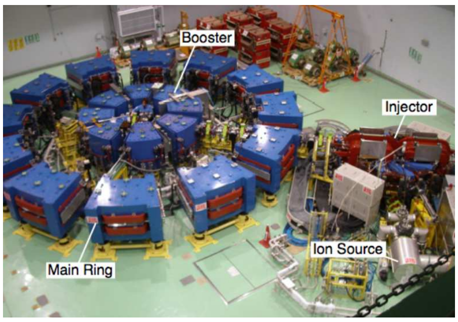

Figure 6: Proton FFAG accelerator assembly.

BNCT

Medical applications of FFAG accelerators have also been proposed in two different fields : hadrontherapy 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 Be target. The growth of the beam emittance and the energy distortion caused by scattering in the target can be controlled using ionization cooling, a functionality which could not be used in a cyclotron due to the lack of space. The whole system has been completed (Fig. 7) and recently the beam was successfully accumulated in the ring with ~1000 turn lifetime as expected.

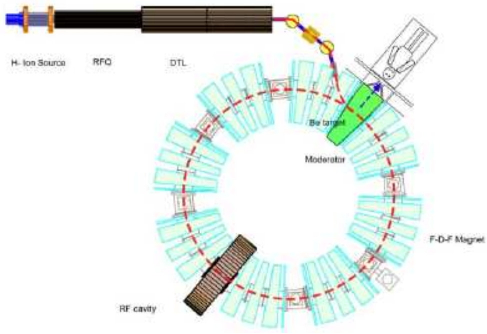

Figure 7: A scheme of the Energy Recovery Internal Target BNCT assembly, based on a radial, FDF lattice FFAG.

Neutron production has already been observed. This is the first experimental demonstration of the efficiency of ionization cooling.

MUON BEAM CAPTURE AND COMPRESSION

PRISM is an experimental proposal of the University of Osaka to build a highly-intense muon source using the 50 GeV proton beam of the J-PARC synchrotron (shown in Fig. 1). In the PRISM project, longitudinal phase space rotation to narrow the initial energy spread of a muon beam by a scaling FFAG ring - featuring a large energy acceptance - has been developed to search for the lepton flavor 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.

NUCLEAR PHYSICS, MATERIAL SCIENCE

In the University of Kyusyu, a new accelerator facility for various applications, such as nuclear physics and material science, is under construction. The main machine will be a 150 MeV proton FFAG accelerator whose design closely follows the one of KEK as presented above (Fig. 4).

EMMA

In the UK, non-scaling FFAGs are currently being studied for a variety of applications, including hadrontherapy,

Figure 8: 6-cell development PRISM ring at Osaka University.

Accelerator Driven Systems and for the rapid acceleration of muons for a Neutrino Factory and a Muon Collider. The unique features of these machines, however, mean that detailed development for these applications requires the construction of a proof-of-principle accelerator to fully explore the beam dynamics, gain experience in non-scaling FFAG design and construction and benchmark the computer codes employed in the studies. This proof-of-principle machine is called EMMA the Electron Model for Many Applications and is being built at the STFC Daresbury Laboratory in the UK.

EMMA has been funded as part of BASROC British Accelerator Science and Radiation Oncology Consortium. Also funded are the design of a non-scaling FFAG (PAMELA) for the acceleration of carbon ions and protons for hadrontherapy and the study of other potential applications of this technology. Details can be found at http://basroc.rl.ac.uk.

EMMA will be a 10-20 MeV electron linear non-scaling FFAG. It has been designed with the necessary flexibility to allow the detailed studies required. In addition, it will use ALICE (Accelerators and Lasers In Combined Experiments) as an injector, Fig. 9. ALICE is able to deliver beams at any energy between 10 and 20 MeV, a very important requirement for a complete study of resonance crossings in EMMA.

EMMA will use a doublet lattice (Fig. 10) 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. Due to the experimental nature of the accelerator it is very important to have sufficient diagnostic devices. Within the EMMA ring, there will be two beam position monitors in each cell, two sets of wire scanners and motorized screens and a wall current monitor. The ring will be surrounded by a beam loss monitor, segmented into four sections. A number of measurements can only be made outside the ring and hence an extraction line has been designed which includes emittance, longitudinal beam profile and momentum measurements. The injection line will also be instrumented to measure the

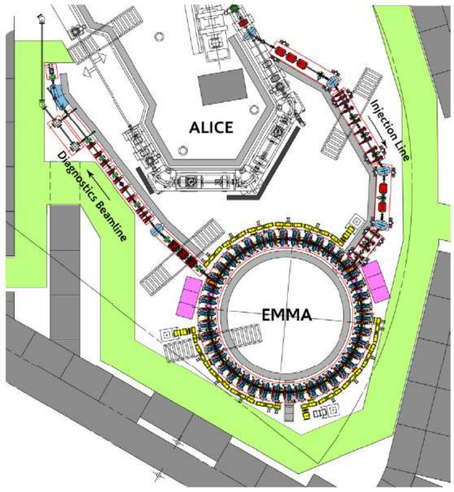

Figure 9: EMMA ring next to its injector ALICE.

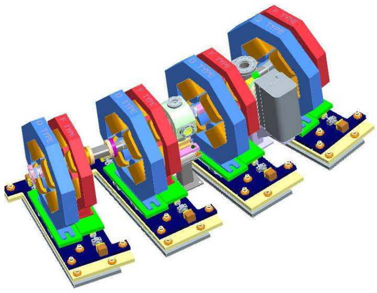

Figure 10: A series of EMMA FD doublet cells.

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 been built and tested and construction of the others will be done during the year. Construction of the machine itself is expected to be finished towards the end of 2009.

HADRONTHERAPY R&D

Scaling spiral sector FFAGs are now seen as good candidates for hadrontherapy applications, with various potential advantages compared to cyclotrons, such as variable extracted energy, or high repetition rate and simplicity when compared to synchrotrons. These considerations have motivated the RACCAM R&D project (Recherche en Accélérateurs et Applications Médicales), based at LPSC in Grenoble (UJF-CNRS/IN2P3) that has received a grant over the 2006-2008 period, from the French National Research Agency (ANR). The RACCAM project aims at producing a preliminary design study of a variable energy proton installation, based on a variable energy, 5 to 15 MeV H- injector cyclotron followed by a spiral lattice FFAG ring with 70 to 180 MeV extraction energy. This study is now close to completion. The project also includes the prototyping of a spiral magnet capable of delivering the required $B \sim r^k$ field law. A magnet of this type is now under measurements at SIGMAPHI, Fig. 11.

Figure 11: Prototype spiral FFAG magnet, under measurement at SigmaPhi.

While starting in 2005 as a collaboration between the LPSC Laboratory in Grenoble, the Radiotherapy Department of the Grenoble University Hospital, and the magnet constructor SIGMAPHI, the RACCAM collaboration has rapidly expanded to include IBA, the AIMA-Development Company, and the Antoine Lacassagne protontherapy clinic in Nice. Preliminary studies have led to a prototype protontherapy accelerator project (Fig. 12).

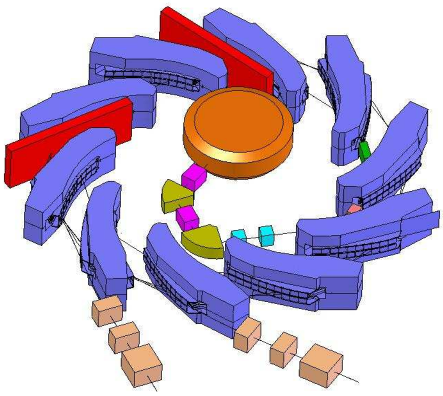

Figure 12: Variable energy, multiple extraction protontherapy demonstrator design.

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.

Details of the RACCAM collaboration can be found on http://lpsc.in2p3.fr/service_accelerateurs/raccam.htm.

CONCLUSION

The international accelerator community is rapidly gaining knowledge of FFAGs and of their rich potential. 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.

REFERENCES

[1] O CAMELOT ! A Memoir Of The MURA Years (Section 7.1), F.T. Cole, Proc. Cycl. Conf, April 11, 1994 ; FFAG particle accelerators, K.R. Symon et als., Phys.Rev. Vol.103-6, 1837-1859, 1956.

[2] Accelerator design concept for future neutrino facilities, J. S. Berg et als., RAL-TR-2007-23. http://www.cap.bnl.gov/mumu/project/ISS/ISS-AcceleratorWG-final.pdf.

[3] CARE-HHH 2004 Workshop, CERN, Sept. 2004.

[4] A link to the FFAG workshops series : http://www.triumf.ca/ffag2004/links.html.