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# *Brief History of FFAG Accelerators*

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# Brief History of FFAG Accelerators

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Few times colleagues of mine have asked me few times why we have today so much interest in Fixed-Field Alternating-Gradient (FFAG) accelerators when these were invented a long time ago, and have always been ignored since then. I try here to give a reply with a short history of FFAG accelerators, at least as I know it. I take also the opportunity to clarify few definitions.

FFAG accelerators were invented about half a century ago independently by K. Symon [1] and T. Ohkawa [2]. Two electron prototypes were built and operated at the end of the 50's and the beginning of the 60's to demonstrate the principles of operation at MURA, Madison, Wisconsin [3-5]. One prototype was a 120-keV Spiral Sector FFAG betatron, and the other a 400-keV Radial Sector FFAG also betatron. A higher-energy prototype of around 50 MeV [6] was also subsequently built, but the project was discontinued because it was soon found to be difficult to operate. The concept of FFAG accelerators were consequently abandoned also because they seemed to require the construction of very complex magnets of large dimensions and weight, and because the cost appeared to be exceedingly too high. Indeed, at those times in the quest of an accelerator capable of several tens of GeV proton beams, FFAG accelerators did not fare well, in cost, size and performance, when compared to more conventional Alternating-Gradient (AG) accelerators like the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory (BNL) [7] and the Proton Synchrotron (CPS) at CERN in Geneva, Switzerland [8], or even compared to the Zero-Gradient Synchrotron [ZGS] at Argonne National Laboratory (ANL) [9]. The first two accelerators were (and still are) capable to accelerate protons to about 30 GeV. The ZGS, now discontinued, could accelerate protons to 12 GeV.

Circular accelerators have two main components: magnets to bring the beam around along a circular orbit, and some sort of electro-magnetic field that provides energy gain. About half-century ago, at the time when FFAG accelerators were invented, there were Fixed-Field (FF) accelerators like Microtrons and Cyclotrons [10] (see Figure 1). To provide stability of transverse motion, magnets had also a gradient field profile, constant along the longitudinal direction of motion. The resulting focusing was thus weak. The advantage of these accelerators was that the magnetic field did not have to vary with the particle energy, and their design was simpler by avoiding eddy-current effects that also simplified the design of the vacuum system. Nevertheless, their maximum energy was limited, they were of large dimensions, and costly. Moreover there were no ways for insertions that were needed for a variety of use. There were also Varying Field (VF) accelerators like Betatrons and Weak-Focusing Synchrotrons [10]. Also these accelerators suffered similar limitations.

The principle of AG discovered also about half a century ago [11], allowed stronger focusing of the transverse motion and thus magnets of smaller size and more compact, and the possibility of reaching higher energies. The AG principle was applied first to Synchrotrons, and then to Cyclotrons. In the latter case, the addition of the AG principle lead to the new concept of FFAG accelerators. In the meantime, it was also realized that focusing can be provided by shaping the entrance and exit angles of the bending magnets. The resulting focusing is weaker than that obtained from a field gradient in the body of the magnets, but in some cases it was found to be very useful. That lead to the design, construction and operation of the ZGS at ANL [9]. In this accelerator the bending magnets have a flat field profile in the body, and focusing is provided only at the entrance and exit of the magnets. This type of edge-focusing would soon be adopted in spiral-shaped magnets as an alternative to radial focusing in the magnet body, from which the spiral-sector FFAG and the radial-sector FFAG (see Figure 2) prototypes built at MURA about half a century ago. The early concept of FFAG did not allow much of drift space, and acceleration was provided by the superposition of a magnetic core where the field varies with time and induces a longitudinal accelerating field. These were called FFAG Betatrons. Later the concept evolved with new design of compact RF cavities that could be installed in drifts of moderate length between magnets. These were called FFAG Synchrotrons. Accelerators that make use of the method of acceleration as in Cyclotrons made of several AG sectors (either spiral or radial) with accelerating RF fields between sectors can be called AG Cyclotrons.

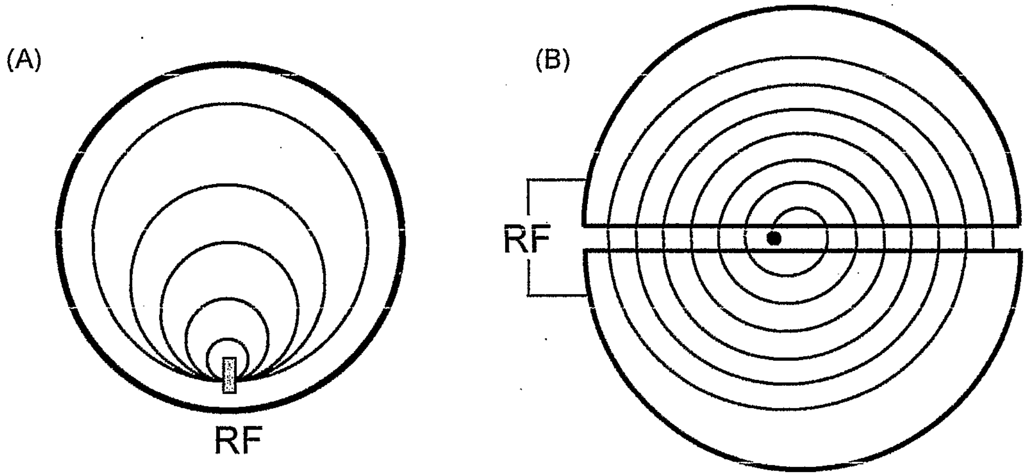

Figure 1. Sketch of a Microtron (A) where all the trajectories with increasing radii go through the same location of the accelerating RF cavity, and of a Cyclotron (B) where the trajectories spiral toward to larger radii and traverse a region where RF accelerating field is applied.

FFAG accelerators were reconsidered briefly about 20 years ago in connection of Pulsed Spallation Neutron Sources [12]. But again also at that time they were not endorsed or approved by the community because judged too expensive and of too cumbersome design and construction. Rapid Cycling Synchrotrons (RCS) and Super

Conducting Linacs (SCL) were more attractive. Since then FFAG accelerators have been rarely discussed.

About ten years ago, FFAG accelerators were reconsidered in connection of acceleration of muons for Neutrino Factories (NF) and for Muon Colliders (μC). It was indeed required to accelerate muons to an energy of about 20 GeV, and the acceleration had to be done very fast because of the very short lifetime of the particles [13]. Several types of accelerators were considered. RCS were rejected because too slow. SCL have been a possibility, but because of the very large betatron emittance, even after cooling, a 200-MHz RF cavity system was required that made the design of the linac very complicated and costly. A Re-circulating Linac (RL) a' la CEBAF was also considered, but it was found impossible to separate the beam at different passes in the arcs, again because of the very large betatron emittance. A FFAG ring was then proposed as the ultimate possibility for the fast acceleration of muons. This indeed can be thought as a linac broken in segments joined together by common arcs. As the beam is accelerated, it travels several turns in the same bending magnets that thus must have very large aperture. At the moment FFAG accelerators appear to be the only possible method to accelerate muons, and thus projects like NF and μC depend on their demonstration. And with the muons FFAG accelerators were recently back in business.

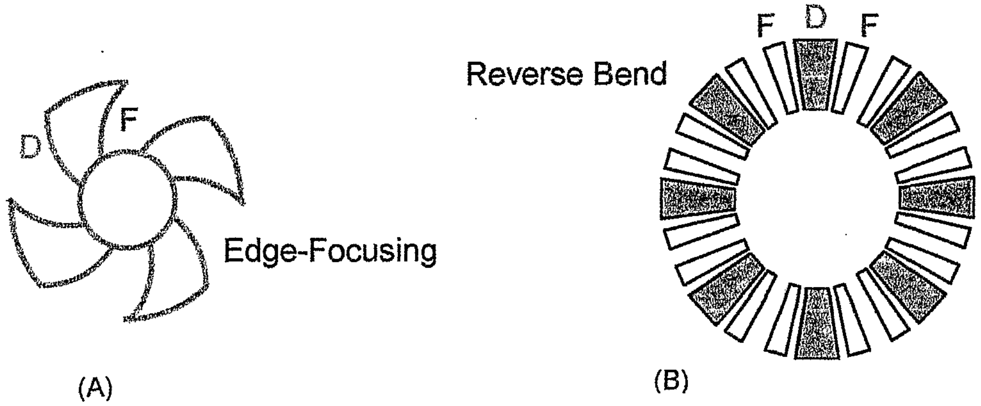

Figure 2. A Spiral (A) and a Radial (B) FFAG accelerator

Soon after, a group of experts from Europe, America and Asia initiated a series of meeting with the main goal to discuss acceleration of muons in FFAG accelerators. These meetings are still taking place in the format of Workshops held about semi-annually, once in America or Europe, and once, usually in fall in Japan [14]. But in the quest of a FFAG accelerator for muons, a problem appeared that had to be solved. It was already known, also fifty years ago, that a magnetic lattice with a Linear AG, already defined at that time as a Non-Scaling Lattice (NSL), had the undesired property of a rapidly changing lattice parameters, like betatron tunes, with the particle momentum [15, 16]. The change over the required momentum range was so large that it was not possible to avoid the crossing of several integral and half-integral resonances. At that time there was a considerable concern about the beam stability and loss when crossing such low-order resonances that the idea of using the NSL was abandoned in favor of a Scaling Lattice (SL) where the radial field had a non-linear profile to compensate for the horizontal chromaticity [17]. In summary, FFAG with SL have the good property of zero radial chromaticity, but require large magnet physical aperture. They need large bending field, do not easily allow long insertions, and are not suitable for large energies since they are costly. On the other side, FFAG with NSL are more attractive because, for the same momentum range, they are more compact and economical. They also allow longer insertions, and are suitable for large energies. But unfortunately they have also large un-corrected chromaticity. This remains the main dilemma confronting the experts in their search for a FFAG accelerator for muons.

There are other issues that were in the meantime discovered and that needed to be addressed. Because of their very short lifetime muons are to be accelerated very fast possibly with the use of superconducting cavities and within very few revolutions. This raised the issue of minimizing the transit time factors, forcing one to chose a lattice operating with a transition energy exactly equal to the central beam energy. Moreover, to get fast acceleration for a beam with such large longitudinal phase space, it has been proposed to accelerate outside and along the separatrix of the RF buckets (Gutter Acceleration) [18].

In the meantime two proton FFAG prototypes were built, commissioned and operated at KEK, Japan, to demonstrate the principle of operation of SL FFAG synchrotrons [19]. The prototypes had energies 0.5 and 150 MeV respectively. It was natural that then the interest on FFAG accelerators included applications with protons like high-power proton drivers for tritium and neutron production, waste transmutation, driving a sub-critical reactor to produce energy, radioisotopes and medical applications [20]. Recently thus the semi-annual collaboration meetings dealt with acceleration of muons in parallel with that of protons. A high-power proton FFAG driver could also be the source for muon production for NF [21] , μC and Neutrino Superbeams [22].

For both type of beams the shown preference so far has been a NSL. Yet there are major differences in the dynamics of motion. Muons have essentially constant velocity during acceleration; they have considerably large betatron and longitudinal emittance; acceleration is exceedingly fast and the beam circulates for no more than ten revolutions; superconducting large-gradient cavities are used; isochronism of motion across the full momentum aperture is crucial; the intensity is relatively modest; and finally acceleration occurs skirting the RF buckets from outside. On the other side, protons have a varying velocity during acceleration that thus has to be done inside the RF buckets; the most obvious approach is the use of ferrite or magnetic alloy for frequency modulation in normal-conducting cavities; the beam will be circulating for about a thousand revolution; isochronism is not an issue since the beam energy is constantly below the lattice transition energy; the beam intensity is high, and space charge forces are strong at injection; yet the normalized beam emittance is much smaller; also the longitudinal phase space area is smaller when compared to the muon beam. A higher-gradient, constant-frequency RF, possibly superconducting, can also be used for acceleration of protons with the principle of harmonic number jump [23]. In this case acceleration is faster and the beam circulates few hundred of revolutions.

But with NSL both cases of beam, muons and protons, need to survive crossing a large number of integral and half-integral resonances. This is by far the most overriding concern. Crossing of multiple resonances without beam loss or degradation need to be demonstrated. At that purpose electron models of reduced dimensions and scope have been recently proposed for both muon and proton beams [24, 25].

It was mainly because of my interest in the acceleration of protons for several applications that I joined the FFAG collaboration study group.

## References

[1] K. Symon et al., Phys. Rev. **103**, 1837 (1956)
[2] T. Ohkawa, Rev. Sci. Instr. **29**, 108, (1958)
[3] L.W. Jones and K.M. Terwilliger, CERN Symposium, Switzerland, June 1956, p. 359
[4] D. W. Kerst, CERN Symposium, Geneva, Switzerland, June 1956, p. 366.
[5] The MURA Staff, Proc. of 1961 Int. Conf. on High Energy Acc. p. 344, Brookhaven.
[6] C.D. Curtis et al., Proc. of Int. Conf. on High Energy Acc. p. 815, Dubna 1963.
[7] The AGS Staff, Proc. of 1961 Int. Conf. on High Energy Acc., p. 39, Brookhaven.
[8] M.G.N. Hine & P. Germain, Proc. of 1961 Int. Conf. on High Energy Acc., p. 25.
[9] E.A. Crosbie et al., CERN Symposium, Geneva, Switzerland, June 1956, p. 42 (ZGS).
[10] Principles of Particle Accelerators, E. Persico, W.A. Benjamin, Inc., NY, NY, 1968.
[11] E.D. Courant & H.S. Snyder, Annals of Physics, **3**, 1-48 (1958).
[12] R. L. Kustom et al., IEEE Trans. on Nuclear Science, Vol. NS-32, No. 5, Oct. 1985.
[13] http://www.cap.bnl.gov/mumu/studyii
[14] http://hadron.kek.jp/FFAG/FFAG05_HP
[15] F.T. Cole at al., Nuclear Instr. and Methods, 25, 189 (1964)
[16] L.C. Teng, Rev. of Sci. Instr., Vol. 27, No. 12, page 1051. (1956)
[17] L.J. Laslett and K.R. Symon, CERN Symposium 1956, Vol. 1, page 279
[18] http://hadron.kek.jp/FFAG/FFAG05_HP
[19] S. Machida et al., Proc. of 2004 EPAC, page 1943, Lucerne, Switzerland, June 2004.
[20] A.G. Ruggiero, Proc. ICFA-HB2004 Workshop, p. 324, Bensheim, Germany, 2004.
[21] A.G. Ruggiero, Proc. NuFact05 Workshop, Frascati, Italy, June 2005.
[22] A.G. Ruggiero, Proc. of EPAC-04, page 159, July 6-11, 2004, Lucerne, Switzerland.
[23] A.G. Ruggiero, BNL Internal Report, C-A/AP 218, September 2005.
[24] S.R. Koscielniak & C. Johnstone, Proc. of PAC 2005, p. 3173, Knoxville, Tennessee
[25] Solicitation of Proposals were made through DOE SBIR program.