Summary of the FFAG05 Workshop at KEK

J. Scott Berg

Brookhaven National Laboratory; Building 901A; P. O. Box 5000, Upton, NY 11973-5000

Abstract. The FFAG05 workshop at KEK is one in a series of important annual gatherings of scientists working in the area of fixed field alternating gradient accelerators (FFAGs). At this workshop, we heard of many FFAG designs that are in operation, under construction, and in the planning stages. These machines are being used for a wide variety of applications. We also had a great deal of discussion of some of the theoretical aspects of FFAG design. This paper attempts to give a coherent summary of the workshop, and hopefully serves as an introduction to the more detailed papers in the workshop proceedings.

Keywords: Fixed Field Alternating Gradient Accelerator

INTRODUCTION

This paper will attempt to give a coherent summary of the FFAG05 workshop at KEK. We heard talks and had discussion in two broad areas: descriptions of various machines which are operating, are under construction, or are being proposed. Secondly, we heard talks and had a great deal of discussion on some of the theoretical aspects of FFAG accelerator design.

Since this paper is an attempt to give the reader a feel for the overall thrust of the workshop, there will inevitably be individual contributions which are not mentioned here. This is in all likelihood because they are not about FFAGs in the strictest sense, but touched on areas of interest to FFAG researchers. I urge the reader to examine the contents of the proceedings for such background material, as it may be of great interest in understanding the importance of some of the FFAG applications that are being proposed.

Finally, the reader that is interested in the subject of FFAGs should consult the individual papers in these proceedings for more detail on the various subjects presented here. Those papers will provide you with much more detail and understanding on the projects and subjects that are described here. I apologize in advance for any errors I have made in presenting here the contributions of individual authors. The individual papers should also be consulted for references to the earlier work in these areas.

FFAGS PROPOSED AND OPERATING

The importance of FFAGs is demonstrated by the large number of machines that have been built or are being proposed to be built, and the large number of applications that such machines are being put to.

We heard about the 150 MeV FFAG at KEK, the second proton FFAG prototype built in recent years in Japan (see Fig. 1). The pulse length from the cyclotron, originally 200 μs, has been reduced to match the injection kicker pulse of 10 μs, with an increase in the peak current by a factor of 3 to 4. The RF voltage has been increased. The beam was extracted at 100 MeV. The machine was tested for 100 Hz operation. At 20 Hz, the machine was able to accelerate a current of 0.2 nA. Finally the machine was used to test our understanding of resonance crossing. This machine is a very important demonstration of some essential abilities of the FFAG at useful energies, giving confidence in the ability to use FFAGs in real-world applications.

Probably the most well-known FFAG design with a specific application in mind is the PRISM longitudinal phase rotation FFAG (Fig. 2). Instead of accelerating a beam, this machine is designed to perform a longitudinal phase space rotation; the large energy acceptance of an FFAG allows the rotation of a beam which initially has an extremely large energy spread. At this point, the beam optics and magnet design have been completed. More detailed tracking studies have begun and are continuing (see Fig. 3 for an example), and they are being used to study the effects of magnet errors. The first three magnets are in the process of being constructed. An magnetic alloy core RF system has been proposed which will have a frequency of 5 MHz and a gradient of 200 kV/m. There will initially only be funding for one RF gap per straight; eventually they would like to install 5. A sawtooth waveform seems desirable over a sinusoidal

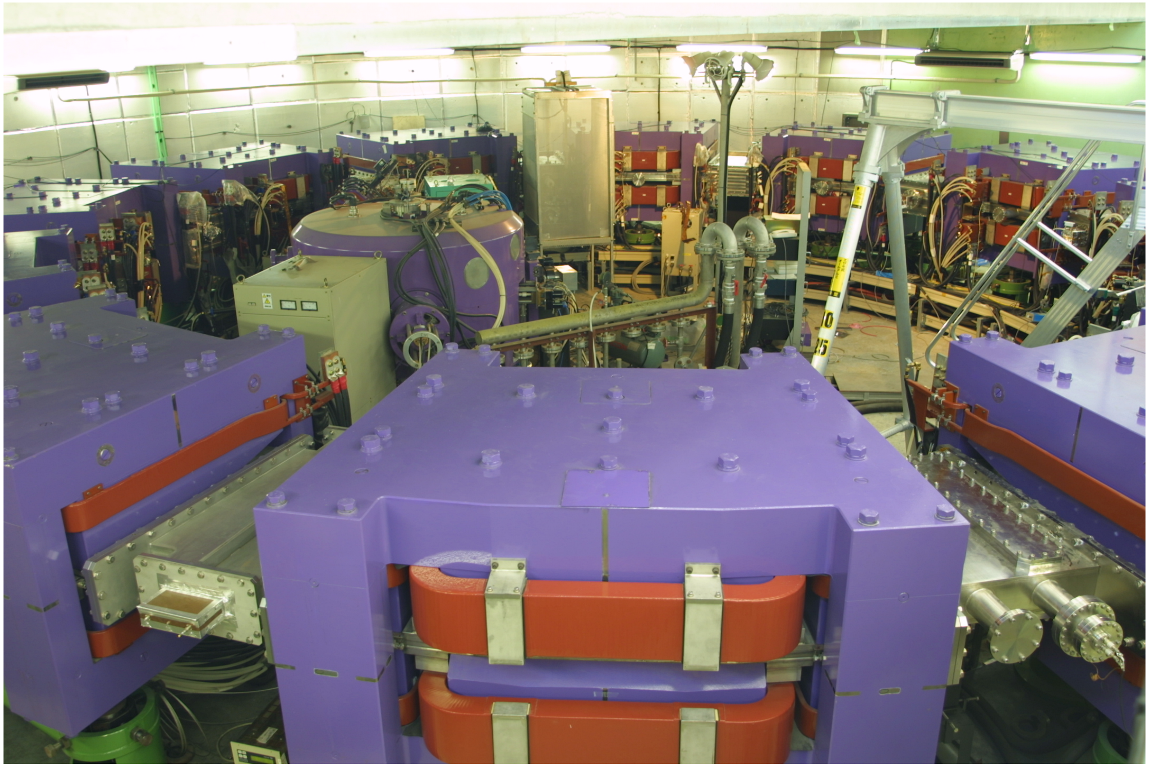

FIGURE 1. Photograph of the 150 MeV FFAG at KEK.

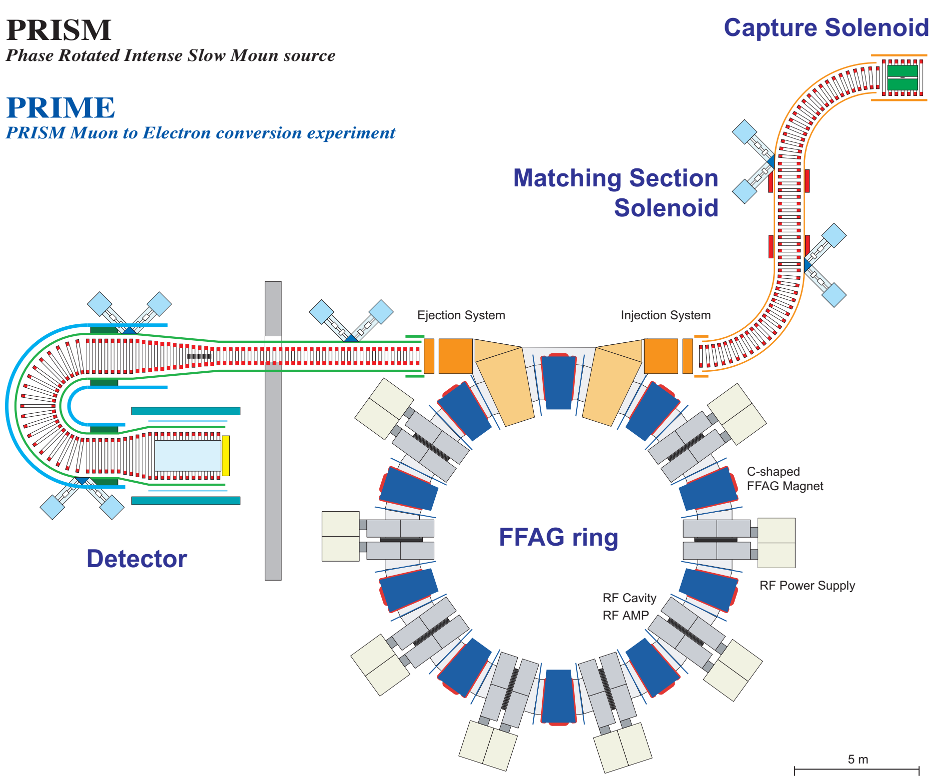

FIGURE 2. The PRISM experiment, with the FFAG shown at the bottom right.

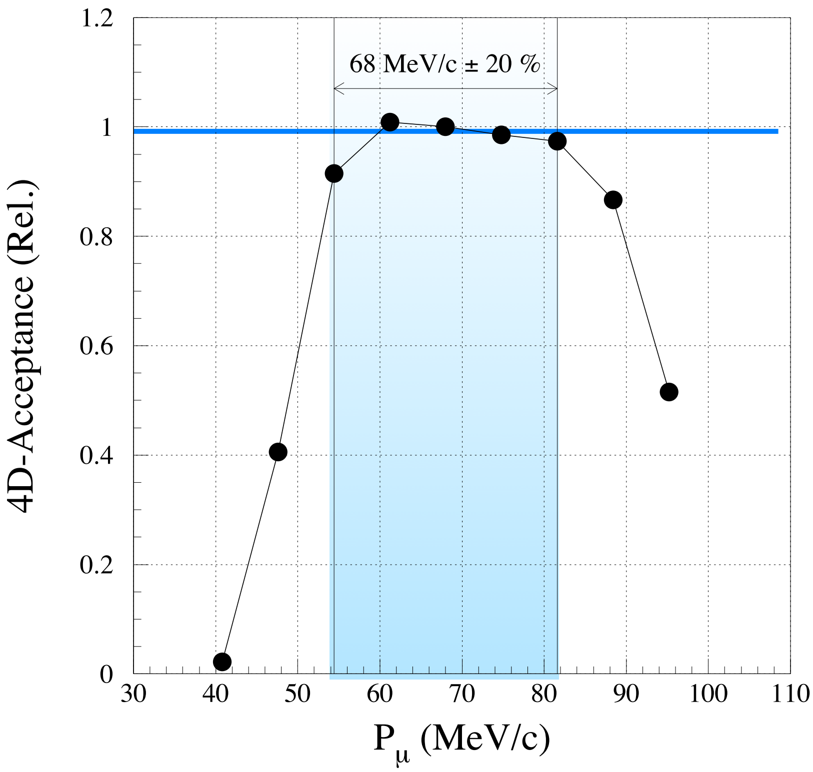

FIGURE 3. Results from tracking studies demonstrating sufficient transverse acceptance over the desired operating energy range of PRISM.

waveform; the details and drawbacks of implementing a sawtooth RF waveform are under study. Vertical injection and extraction systems have been designed and are being studied. Various diagnostic systems have been studied as well. Machine commissioning is expected to begin in 2007.

The institution hosting this workshop, the Kyoto University Research Reactor Institute (KURRI), is in the process of constructing a chain of three FFAGs which will drive a subcritical reactor (Fig. 4). The system will be designed to allow the control of the extraction energy and beam current, thus controlling the output power of the reactor. The initial design for the machine will have a final energy 150 MeV, a current of 1 μA, and operate at 120 Hz. Eventually, the machine will be upgraded to 200 MeV, 100 μA of current, and 1 kHz operation. The three stages are an H^+ spiral FFAG using induction acceleration, accelerating from 100 keV to 2.5 MeV; a second radial sector stage accelerating to 20 MeV; and a final 12-cell radial sector stage accelerating to 150 MeV. The first ("injector") stage has been tested, without trim coils, to 250 keV, and the beam has been extracted. The machine successfully tested crossing of an integer resonance. The magnets for the second "booster" stage are being tested now, with first beam going into the ring in the spring of 2006. The machine may also be used in the future for medical applications.

At KURRI, an FFAG is being proposed for use in a promising cancer treatment method known as boron neutron capture therapy (BNCT) (Fig. 5). A current of at least 20 mA is needed on a target at 10 MeV. The machine will accelerate only to recover losses in the target. Because of energy straggling in the target, the beam is expected to have a large energy spread; thus, an FFAG design is being proposed. The machine will require a 10% energy acceptance and a 1 mm transverse acceptance. Injection into the machine will be at the full 10 MeV energy, with a current of 40 mA. To achieve a desired 90° phase advance per cell, the machine will have 8 sectors. It may be a spiral sector machine to get a longer straight for the target, but that has yet to be decided. The target will be wedge shaped to use non-conservative "emittance exchange" to reduce the rate of growth of the energy spread, at the cost of a growth in the horizontal emittance. This effect will be discussed more in the next section.

There is currently funding available to build a proton therapy facility in the Ibaraki prefecture of Japan, near KEK. Studies have been done on the machine design, which will be finalized in the summer of 2006. The current machine specifications are that it will reach 230 MeV, have 16 FDF cells, straights of at least 1 m, a field index of 13, and

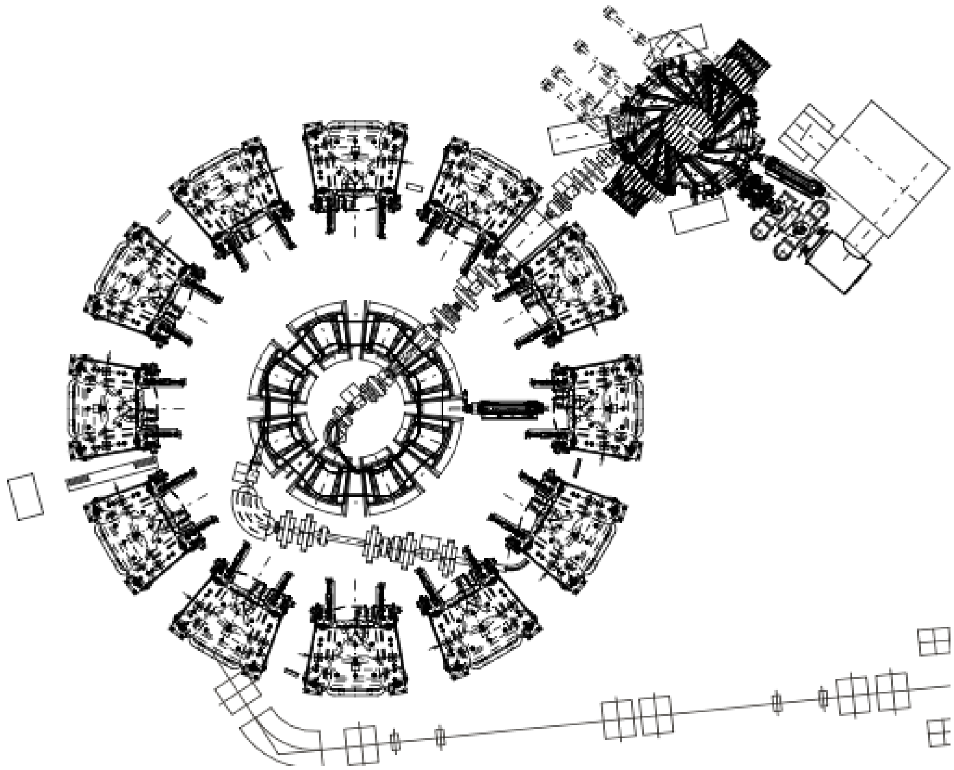

FIGURE 4. The chain of FFAGs that will drive a subcritical reactor at KURRI.

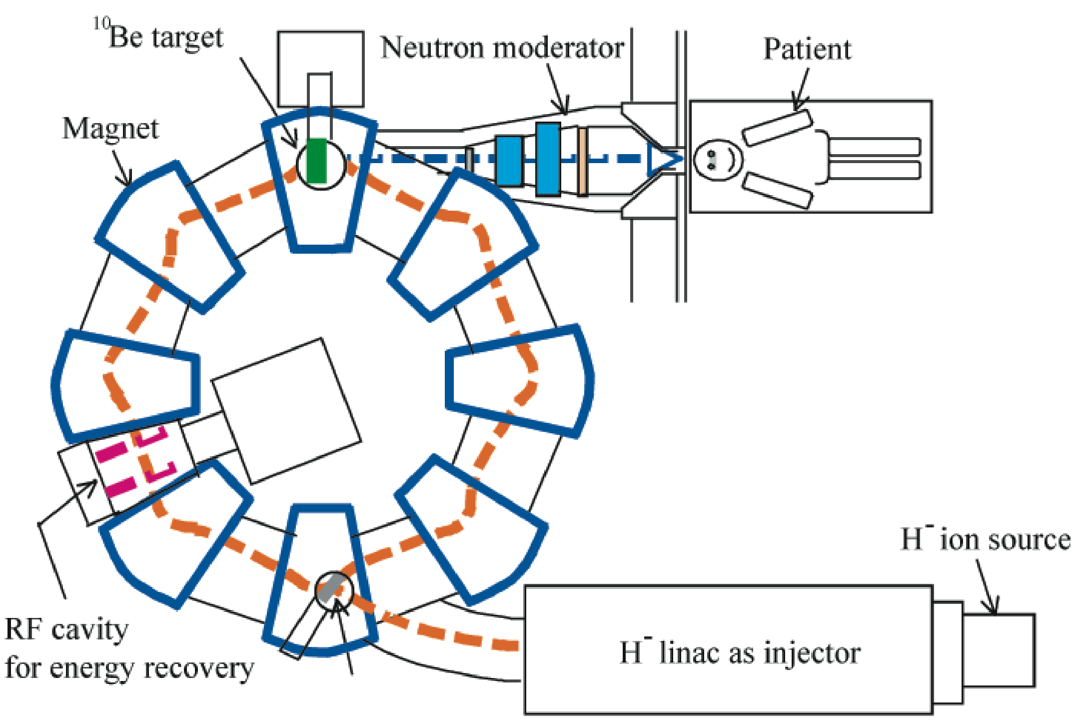

FIGURE 5. Diagram of an FFAG-based boron neutron capture therapy facility.

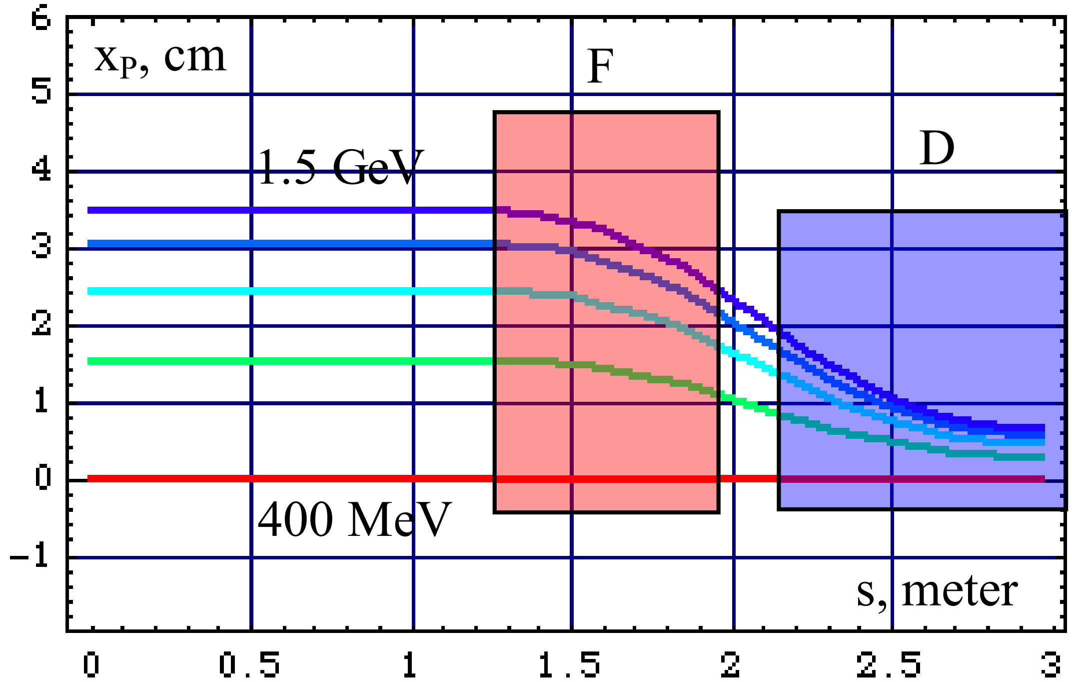

FIGURE 6. Closed orbits in a linear non-scaling FFAG design for proton machines.

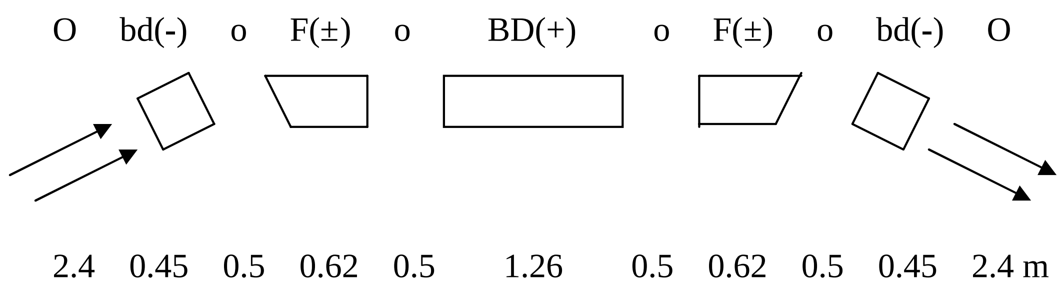

FIGURE 7. Structure of a 5-magnet nonlinear FFAG cell.

operate at 100 Hz with at least 100 nA of current. The FDF cells were chosen to generate a small orbit swing and to make extraction easier. The machine will have a cyclotron H^+ injector with an energy of at least 20 MeV. The machine will have multiple extraction ports, allowing parallel treatments. The beam will be pulsed for spot scanning.

Particularly at high energies, there has been a great deal of interest in recent years in so-called non-scaling FFAGs. Several proton machines were discussed which used a single design as a starting point that was adjusted to the machine requirements using simple scaling laws. The proposed applications were an injector to the AGS at Brookhaven National Laboratory, a 1 GeV 10 MW proton driver, a higher energy proton driver (11.6 GeV) for a neutrino factory, and an electron model to simulate these machines. These machines use linear combined function magnets in an FDF triplet configuration (see Fig. 6). An earlier type of design known as an “adjusted field profile” design which used nonlinear magnets was abandoned due to its large tune shift with amplitude. Two types of RF systems for these machines were discussed: a traditional scheme where the RF frequency varies as the beam accelerates, and a “harmonic number jump” scheme where the energy gain varies with transverse position so as to achieve an integer change in the harmonic number with each turn.

Interest in nonlinear non-scaling FFAGs has not completely disappeared, however. A type of design with a 5-magnet cell was presented (see Fig. 7). The design technique used for these machines can be used to meet several possible conditions: the machine can be made isochronous, the tunes can be made approximately constant, or the machine can

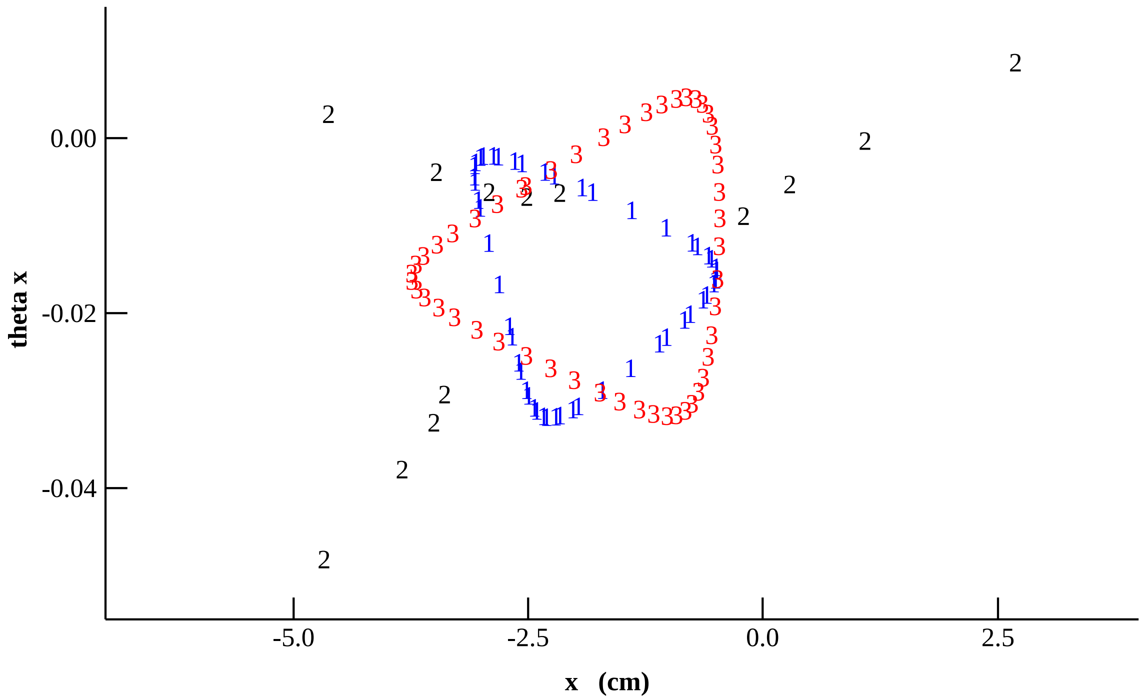

FIGURE 8. Tracking below (1), at (2), and above (3) the energy of a third order resonance for a linear non-scaling FFAG lattice with sextupole fields on the ends of the magnets.

be designed to accommodate insertions. This design is being considered for a proton driver, muon acceleration, and ionization cooling of muons.

Linear non-scaling FFAGs are of potential interest for many applications, but such a machine has never been built. To test whether these machines perform as expected, it would be very useful to built a low-cost model of such a machine. Two machines have been proposed recently: an electron model based on muon acceleration parameters (EMMA), and a proton machine to study the use of a linear non-scaling FFAG in medical applications. The former machine is designed to test the unique acceleration mode that occurs in high-energy linear non-scaling FFAGs with high, fixed RF frequency (in particular, muon FFAGs) and to look at resonance crossing in such a machine. It will use 1.3 GHz RF, accelerate from 10 to 20 MeV, and have 42 cells. The latter machine will have a final kinetic energy in the range of 40 to 100 MeV; it will irradiate tumors in mice to test the performance of this method for cancer treatment, but will also study the feasibility of linear non-scaling FFAGs. In particular, it will look at issues of slow resonance crossing that will occur in linear non-scaling FFAGs that accelerate slowly using low-frequency RF. This medical test machine appears to have good prospects for funding.

There is interest in using FFAGs even beyond the projects described here. More projects seem to keep coming up in Japan. There is interest in using them for a spallation neutron source in Japan. In France, the UK, and other places, there is interest in using them for medical applications, and in that case there appears to be funding becoming available.

DESIGN STUDIES

In addition to many talks about the machines that are being built and proposed, we heard specifically about various aspects of designing FFAGs.

We heard discussions of the use of three tracking codes in studying FFAGs: ZGOUBI, code by Shinji Machida, and ICOOL, as well as some general comments on tracking codes. We saw results of using these codes for the study of scaling FFAGs, linear non-scaling muon FFAGs, EMMA, and isochronous 5-magnet cell FFAG lattices. It was shown that the sextupoles that normally appear at the ends of dipole magnets due to symmetry breaking in the coil

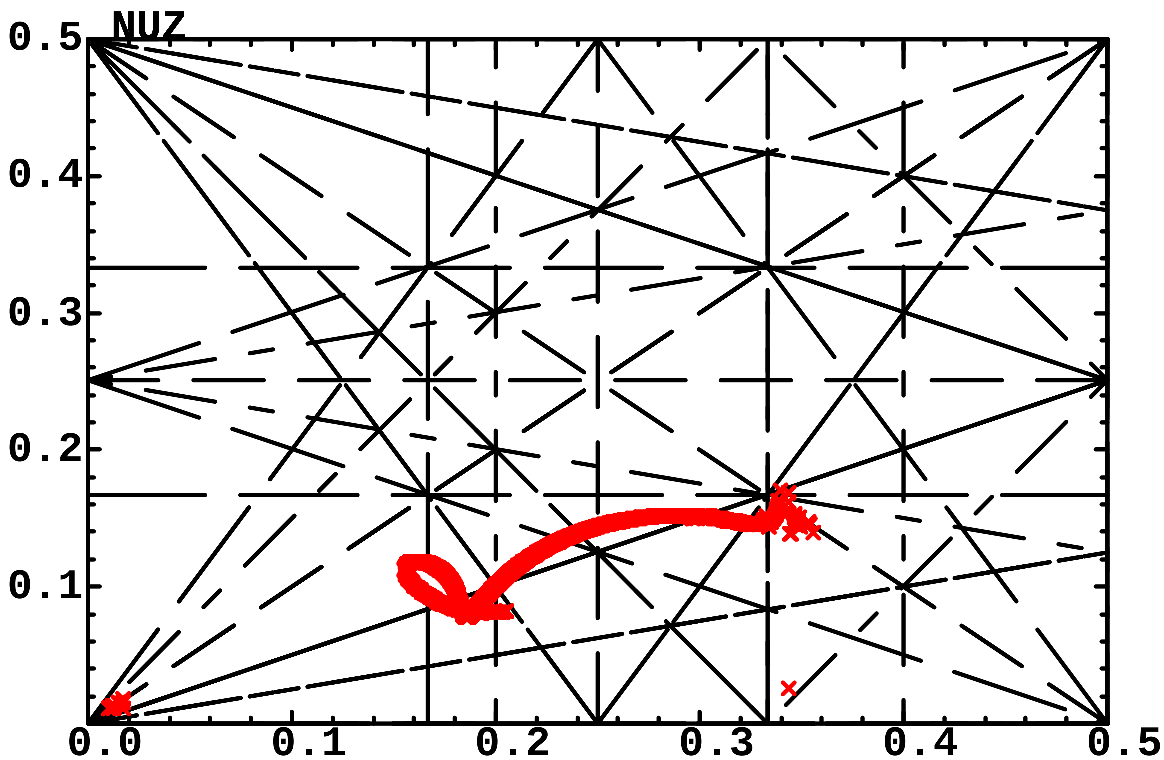

FIGURE 9. Evolution of the tune during acceleration, showing the resonance where beam loss occurs (right).

configuration will cause beam loss if not corrected (see Fig. 8). In the isochronous FFAG, there was significant beam loss during the acceleration cycle due to a resonance crossing, as shown in Fig. 9.

In the linear non-scaling FFAGs, tracking results indicated that for sufficiently large transverse amplitudes, the particles were not successfully accelerated (Fig. 10). This appears to be a result of the time of flight variation with energy depending on the transverse amplitude (Fig. 11). There is a direct relationship between this effect and the tune variation with energy, and this correctly predicted the effect. Initial attempts to correct this by symmetrizing the parabola at high energy didn't work very well. Reduction of the low-energy tune should help, since it will reduce the derivative of the tune with energy.

There was discussion of important features to have in tracking codes for them to correctly model FFAGs. Truncated power series should be used with caution, in particular avoiding a global truncated power series map. Geometry should not be determined by a reference particle that follows the actual magnetic field; geometry should be in a coordinate system that is appropriate to the magnet. Treating magnet ends correctly is important. Finally, when tracking a particular machine, one should consider carefully the initial distribution that one uses: matching can be more complex than in conventional machines.

There was discussion of the theory of resonance crossing; non-scaling machines cross many resonances, and scaling lattices cross resonances because the field is not ideal. A theoretical computation of resonance crossing was shown, and it was demonstrated that the precise effect depends on the direction that the resonance is crossed.

An experimental demonstration of resonance crossing was shown in the 150 MeV FFAG. The resonance was a $3\nu_x = 11$ resonance that is excited by a closed orbit distortion (COD) feed-down. The COD is caused by the cavity core, and can be corrected by dipoles. Beam loss at the resonance crossing was shown, and was successfully corrected by dipoles.

As mentioned previously, a BNCT machine is being proposed which will have an internal target. Energy straggling in that target will lead the energy spread to increase indefinitely. It has been proposed to use a wedge-shaped target to non-symplectically couple the longitudinal plane to the horizontal (Fig. 12). As shown in Fig. 13, as one increases the wedge angle from zero, the longitudinal growth rate decreases, at the cost of an increase in the transverse growth rate. The longitudinal growth rate can be reduced without increasing the transverse emittance beyond acceptable values. If

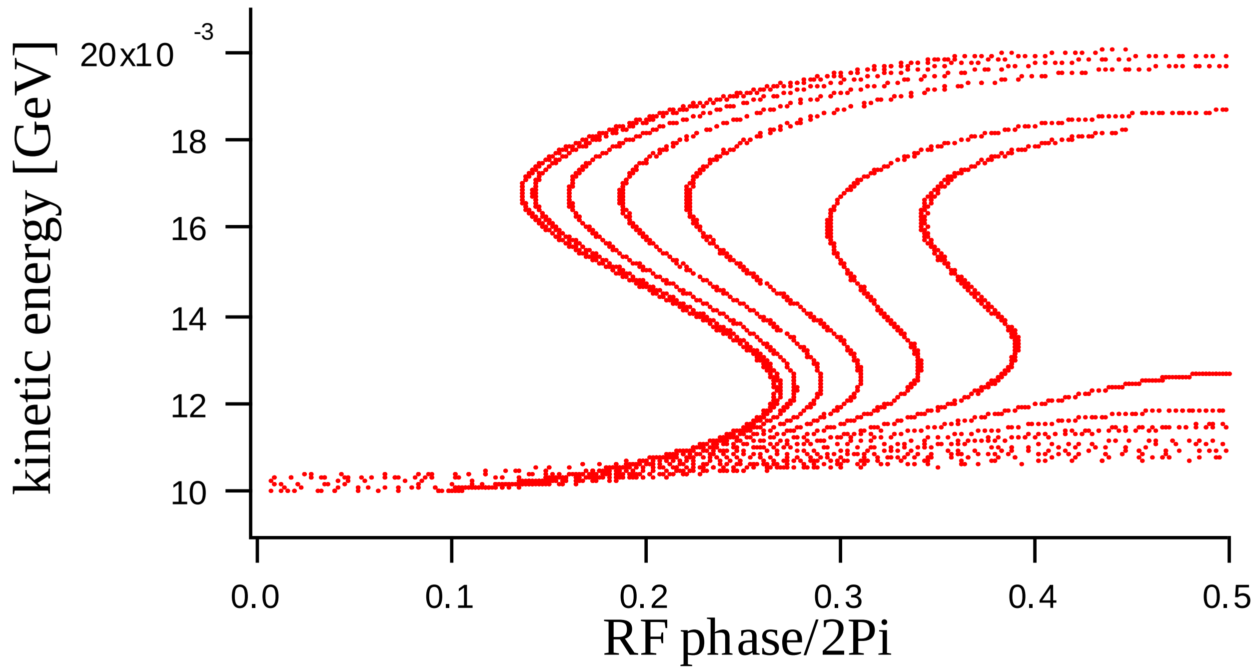

FIGURE 10. Acceleration of particles with different transverse amplitudes. Lines further to the right have larger transverse amplitude.

one could couple the vertical plane as well, one could do even better, but coupling to the vertical plane may break the scaling property of the lattice. There was some discussion of whether electron cooling may be better than this method, since it is more well-tested.

Many FFAGs require magnetic alloy cavities; there was some discussion of the design of these devices. Figure 14 shows that PRISM, and most likely other future FFAGs, will require significantly higher gradients in their cavities than have as yet been achieved. Magnetic alloy cavities are easily saturated by external magnetic fields, and thus those fields must be shielded down to around 100 Gauss. Cooling is one of the biggest problems for high duty factor operation. Higher voltage, higher repetition rate, and higher duty factor all require more cooling power. Several schemes were talked about. For low cooling power, forced air is used. For more cooling, indirect cooling can be used. This doesn't reduce the cavity impedance, and can used for high cavity frequency (20 MHz and up). For even more cooling power, one must use direct water cooling. This allows a high repetition rate, but gives an impedance reduction, and can only be used for low frequencies (below about 4 MHz).

CONCLUSION

Many scaling FFAGs are in the process of being designed, built, and commissioned for many applications. New ideas for better hardware to improve performance continue to be developed. Interest in using FFAGs for many applications continues to grow.

A great deal of design work continues to be done on non-scaling FFAGs. Extensive tracking studies are being done. We are finding problems in those studies, but we believe that we understand them and have good hope of addressing them satisfactorily. Work also continues to be done on the important issue of resonance crossing.

This workshop reminds us of the importance and promise of FFAGs for many accelerator applications. We have extensive understanding of these machines, and will continue to find ways of expanding the applications of these machines. We are continuing studies on ways of improving their performance and reducing their cost. The workshop has been a great success, and we look forward to having more progress to report at the next one.

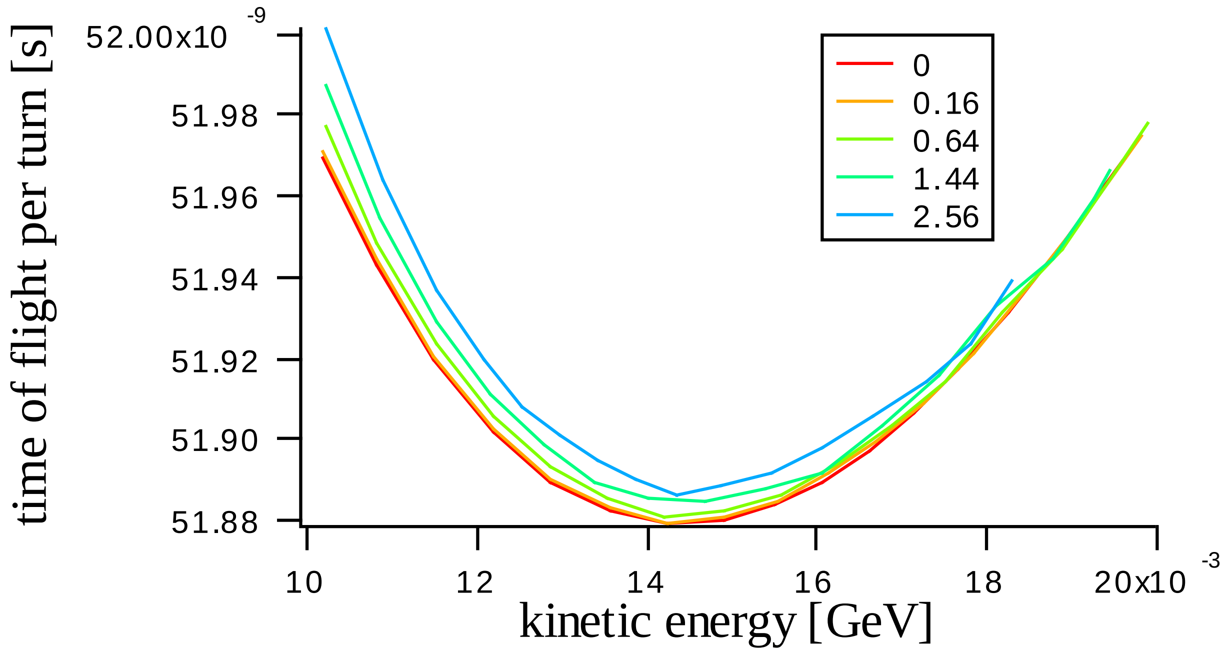

FIGURE 11. Time of flight vs. energy, for different transverse amplitudes.

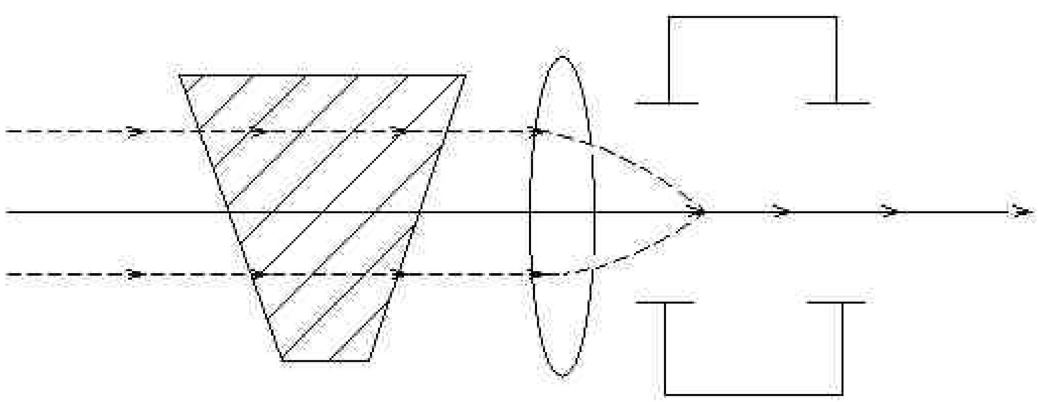

FIGURE 12. How a wedge-shaped absorber couples longitudinal motion to vertical. The wedge is at a point with dispersion, and causes all particles to have approximately the same energy.

ACKNOWLEDGMENTS

I would like to thank the management of the Kyoto University Research Reactor Institute for generously agreeing to host this workshop, and the conference organizer Yoshiharu Mori for running the workshop and for allowing me the privilege of summarizing the workshop. Finally, my work, including the preparation of this paper, has been supported by the United States Department of Energy, Contract No. DE-AC02-98CH10886.

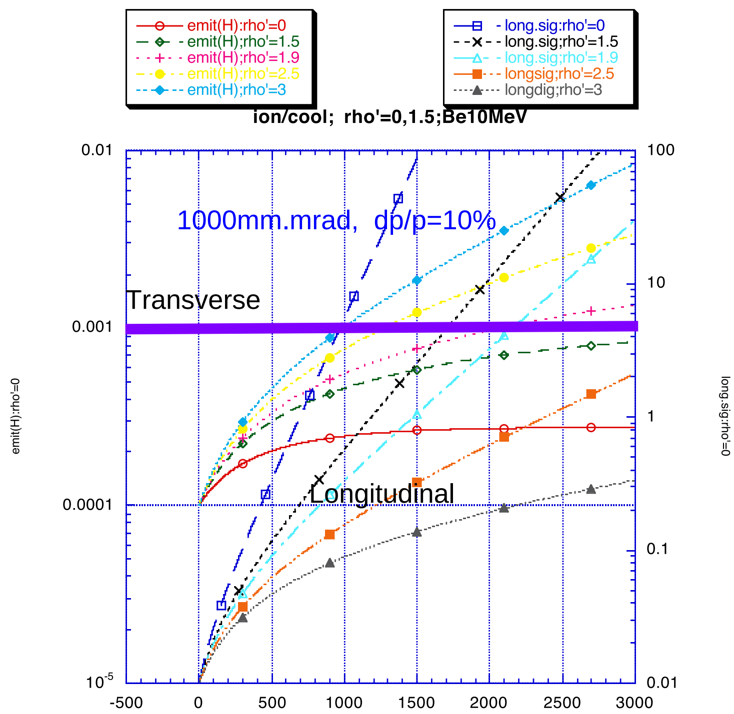

FIGURE 13. Transverse and longitudinal emittance growth for different wedge angles. The horizontal line gives the acceptable values for both quantities.

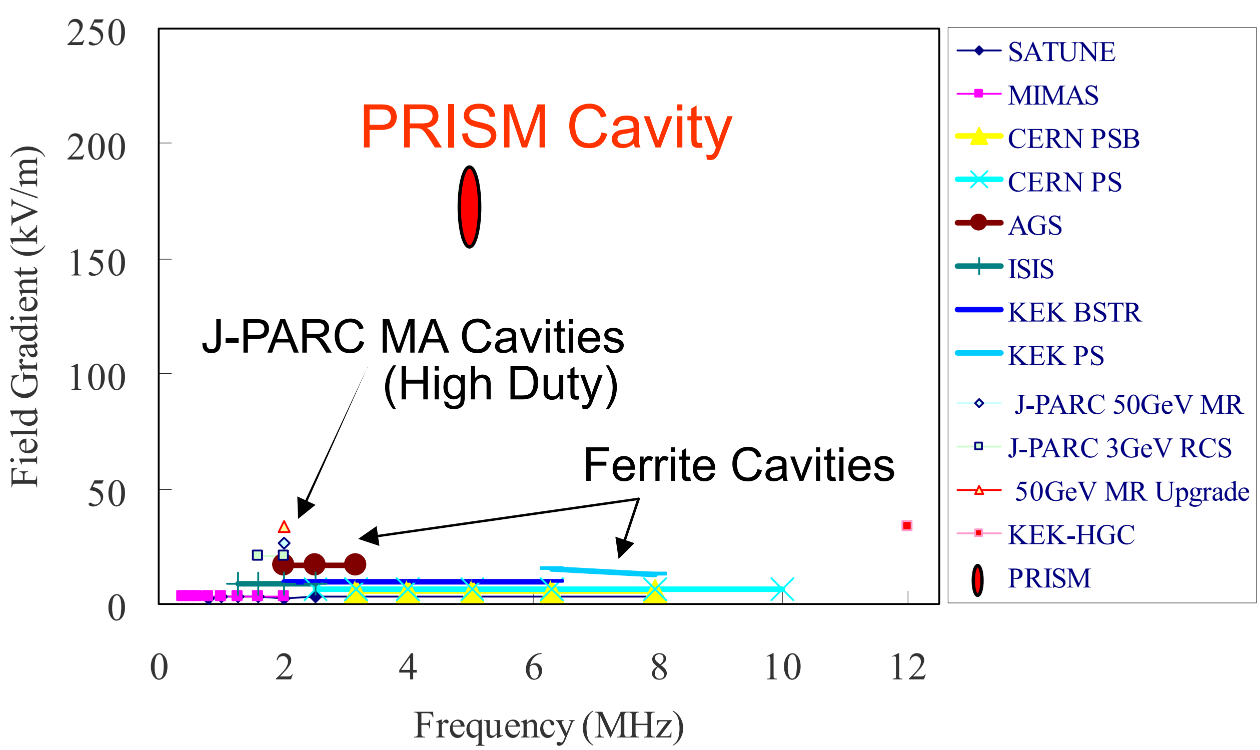

FIGURE 14. Existing cavity gradients, and the PRISM requirements.