MURA DAYS

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Abstract

The Midwestern Universities Research Association (MURA),incorporated in the mid nineteen-fifties, was a unique institution in that, although it never succeeded in its primary goal of building a multi-GeV particle accelerator, it remained in existence for more than ten years, during which the MURA group made many contributions to the science of particle accelerators. Included among these were the invention of fixed field alternating gradient (FFAG) accelerators and spiral sector cyclotrons, an extensive analysis of rf acceleration with particular attention to the consequences of Liouville's theorem, beam stacking, analytic and computational studies of nonlinear orbit theory, studies of collective instabilities, and the first demonstration of practical ways to achieve colliding beams, Although no large FFAG accelerators were ever built, model FFAG accelerators turned out to be excellent devices for the experimental study of accelerator problems because they separate the guide field from the acceleration process. Models were used to study nonlinear resonances, acceleration processes, space charge limits, and beam stacking. Among the last MURA projects was an electron storage ring that became the first machine dedicated exclusively to the production of synchrotron radiation for experiments, a facility which evolved into the highly successful Synchrotron Radiation Center at the University of Wisconsin-Madison.

MURA

The Midwestern Universities Research Association (MURA) was incorporated in 1954 with fifteen universities as members. Its purpose was to promote a large accelerator in the Midwest. In 1956 the MURA working group located in Madison, Wisconsin, the chosen site for a MURA accelerator. During the next thirteen years some 74 MURA employees, graduate students, and staff from MURA universities participated in the working group, making many important contributions to accelerator science. I'll discuss the technical and scientific contributions of MURA, not the political aspects which are also of interest.

FFAG

1954 saw the invention of the Fixed Field Alternating Gradient (FFAG) accelerator. In an FFAG accelerator the guide magnetic field is constant and accommodates all orbits from injection to output energy. Focusing is achieved by means of alternating gradients, a principle which had just been invented. The idea had also occurred to other people. We received a paper from Tihiro Ohkawa in Japan presenting the same idea. Ohkawa was invited to visit and joined the MURA working group.

The advantage of a fixed field machine is that it separates the guide field from the acceleration process. This allows a great variety of acceleration schemes and simplifies accelerator experiments.

Radial Sector Model

The first FFAG configuration proposed was a radial sector accelerator. Figure 1 shows a model which operated in 1956. The injection energy at the inner orbit was 20 keV; the energy at the outer orbit radius at 54 cm was 400 keV. You can see the betatron core which provided a very easy way to accelerate electrons. An experiment, for example an rf acceleration process, could be carried out, and the result observed by betatron accelerating the resulting beam onto a detector.

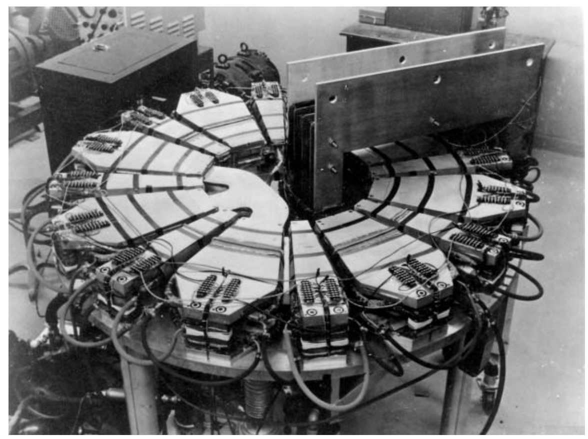

Figure 1: Radial Sector Model.

There are eight sectors, each consisting of a large and a small magnet. The magnetic field increases with radius as R^k, with k=3.36. The field in the smaller magnet is reversed, providing the alternating gradient. This of course makes the orbit circumference about 5 times larger than it would be for a uniform magnetic field.

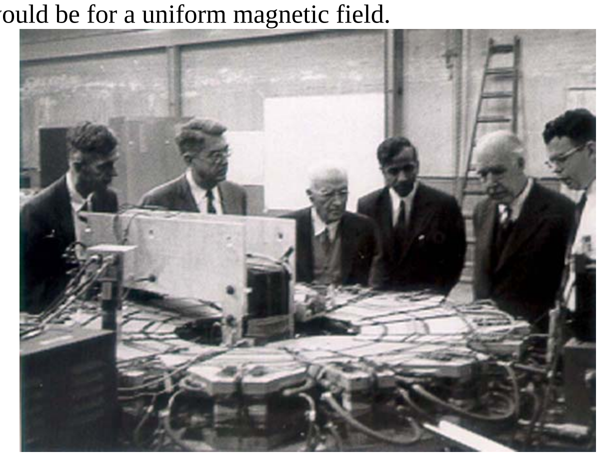

Figure 2: Important Visitors

In order to make the orbits scale in proportion to the radius, it is desirable to have the magnetic field pattern scale in proportion to the radius. This is guaranteed if the magnet gap is proportional to the radius, a solution favored by theorists. The builders preferred to save iron, copper and power by keeping the gap constant and shaping the field by appropriate windings. After a decisionless debate in which we all agreed that either solution would work, we took a vote which came out in favor of geometric scaling of the magnets.

We had a few important visitors who were interested in the model. In Figure 2 you should be able to identify Niels Bohr and Subramanian Chandrasekhar.

Spiral Sector Model

Donald Kerst invented the spiral sector FFAG configuration. Figure 3 shows a spiral sector model which began operation in 1957. Each sector has just one magnet whose edges spiral out in radius. Particles crossing the edges at an angle experience alternating gradient focusing. Because there are no reverse fields, the circumference of the orbit is only about two times that for a uniform field.

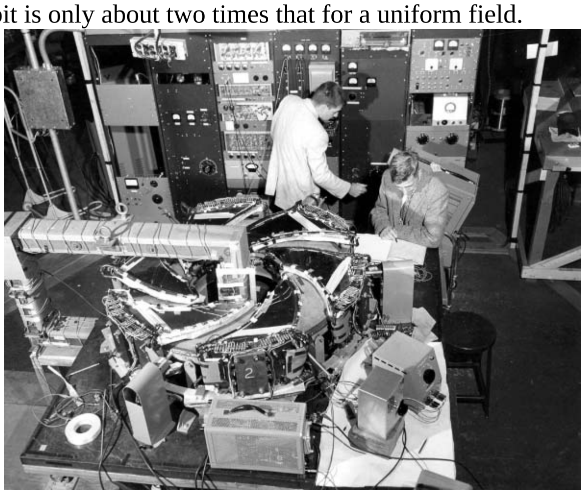

Figure 3: Spiral Sector Model

Jackson Laslett and I worked on the theory of spiral sector orbits. At first we thought the chief advantage of this configuration was that it is sufficiently complicated that it is hard to show that it will not work. But indeed it does work very well.

In designing this model we made detailed analytical and digital computations of orbits and magnetic fields. As a result the machine operated when first turned on, perhaps a record for accelerator construction.

NONLINEAR ORBITS

In most accelerators, magnetic fields are made to vary as linearly as possible, so that nonlinear effects are small perturbations. In FFAG machines nonlinear effects are important and determine the stability limits which determine the maximum allowed oscillation amplitudes.

Experiments were done on both models to check theoretical predictions regarding orbit stability as a function of betatron oscillation frequencies. Figure 4 is a contour plot showing beam intensity in the radial sector model as a function of the number of radial oscillations per revolution plotted horizontally and the number of vertical oscillations per revolution plotted vertically. Theoretically predicted linear and nonlinear resonances lie along the straight lines shown. One can see the wide stop band along the linear resonance ν_x=3, as well as reductions in intensity along other linear and nonlinear resonances. Similar measurements made with the spiral sector model also confirm the predictions of orbit theory.

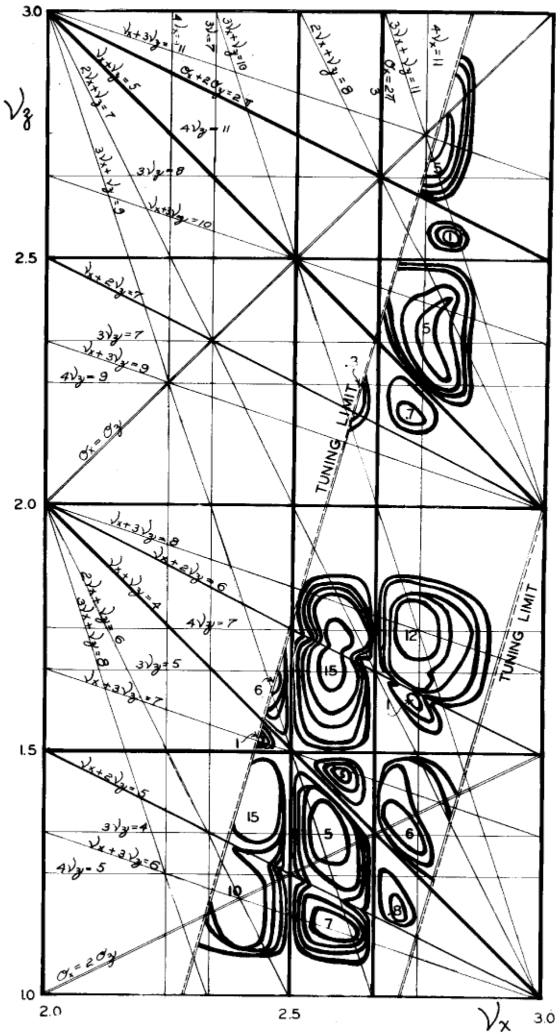

Figure 4: Resonance Survey, Radial Sector Model

Numerical calculations of FFAG orbits often showed apparently random behavior which we called "stochastic" behavior. Such behavior would now be called "chaotic". At first we were not sure whether these effects were real or artifacts of the numerical calculation. We devised exactly canonical numerical algorithms to eliminate the possibility of nonphysical features of the algorithm. We also made extensive checks to guard against round-off errors. We thus convinced ourselves that these stochastic effects are real.

RF ACCELERATION

Fixed field accelerators allow a great variety of rf acceleration schemes. One possibility is beam stacking, where we inject successive beams and accelerate each up to an intermediate energy. Donald Kerst mentioned this to Eugene Wigner who pointed out that Liouville's theorem would be relevant. When he reported this to us, Andrew Sessler and I realized that this was a key to studying rf acceleration processes. We wrote a paper on rf acceleration[1] in which we discussed this and other topics.

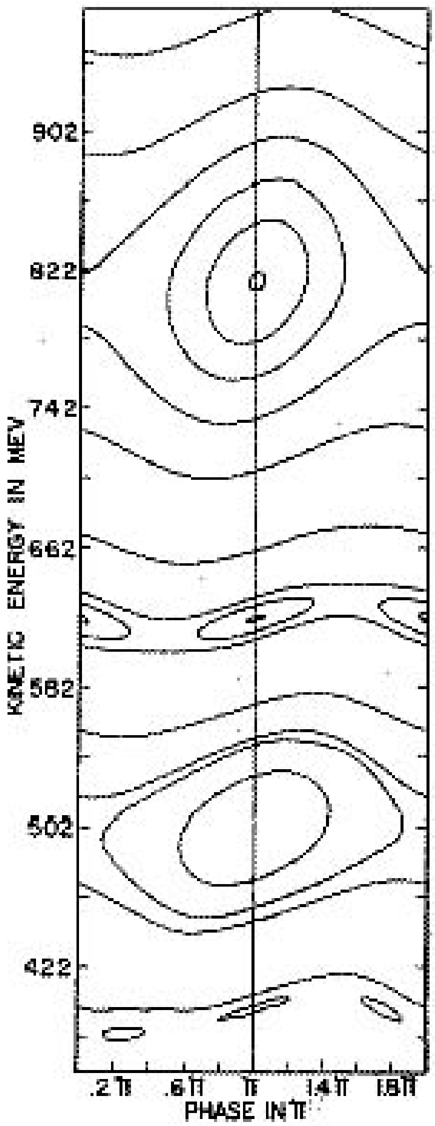

Figure 5: Numerical Simulation of rf Acceleration

Figure 5 shows the results of a numerical simulation of an rf acceleration process in which the radio frequency and voltage are fixed. Once per revolution we plot a point at the particle energy and the rf phase when the particle arrives at the accelerating gap. There is a fixed point at phase π, energy 500 MeV, where the radio frequency is 9 times the revolution frequency, and another at 814 MeV where the radio frequency is 10 times the revolution frequency. Both points are surrounded by trapping regions where the points lie on closed curves surrounding the fixed points. If we were to change the radio frequency slowly, the trapped phase points would be carried up or down in energy. This suggested to me using a high harmonic number so that there are a number of trapping regions between the injection and output energy. By modulating the frequency, these regions could be moved upward past the injector so as to carry injected particles to the output energy. I called this scheme a "bucket lift" in analogy with the devices used by farmers to load hay or grain into their barns. The trapping regions were then called "buckets", a name which is still in use, although no bucket lift accelerator was ever constructed.

Because of Liouville's theorem, the phase points in any rf acceleration process move like an incompressible (two-dimensional) fluid. This makes the name "bucket" even more appropriate. An interesting consequence is that if the buckets are moved upward, the surrounding untrapped phase space must on average move downward. We call this "phase displacement".

Beam stacking experiments were carried out on the FFAG models. Figure 6 shows the results for the radial sector model. These are oscillographs of beam intensity vs. energy. Because of the way the experiments were carried out, energy increases toward the left. The first trace shows an injected beam at an initial energy. The beam is captured in a bucket and accelerated up to a higher energy. The result is shown in the second trace where we also see a little untrapped beam remaining at the initial energy. In contrast to actual beam stacking, in this experiment we did not inject successive beams, but simply carried out successive rf cycles. The result after 4 cycles is shown in the third trace. We see that the result of four cycles is to accelerate most of the remaining beam and to displace the first beam down in energy.

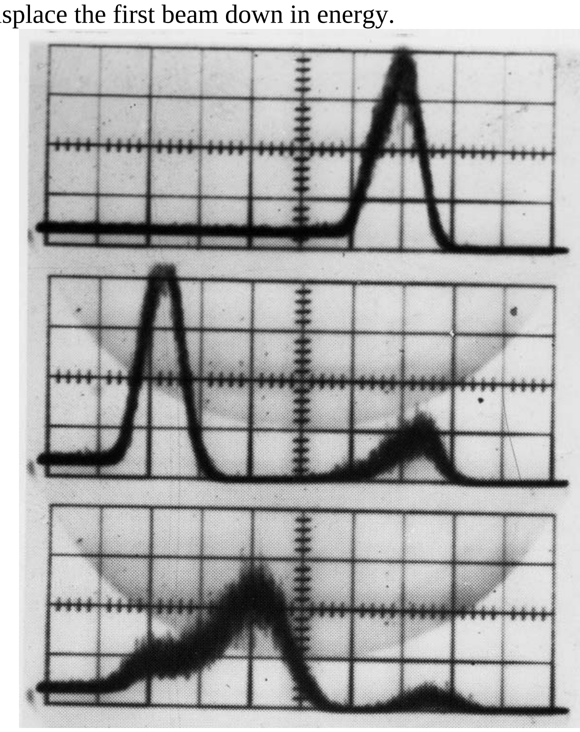

Figure 6: Beam Stacking Experiment

Among other topics studied theoretically and experimentally by the MURA group are acceleration of buckets, phase displacement, capture of a beam in an expanding bucket, and acceleration across the transition energy.

With high rf voltages, we observed stochastic phenomena near the boundaries of a bucket, as shown in Figure 7. On the hypothesis that stochastic phenomena occur when bucket boundaries overlap, we ran a case with two nearby rf frequencies with voltages such that the predicted buckets would overlap. The results in Figure 8 give totally chaotic orbits. The solid curves are the predicted bucket boundaries.

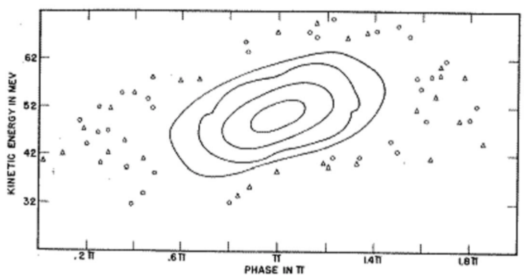

Figure 7: Stochastic behavior near bucket boundary

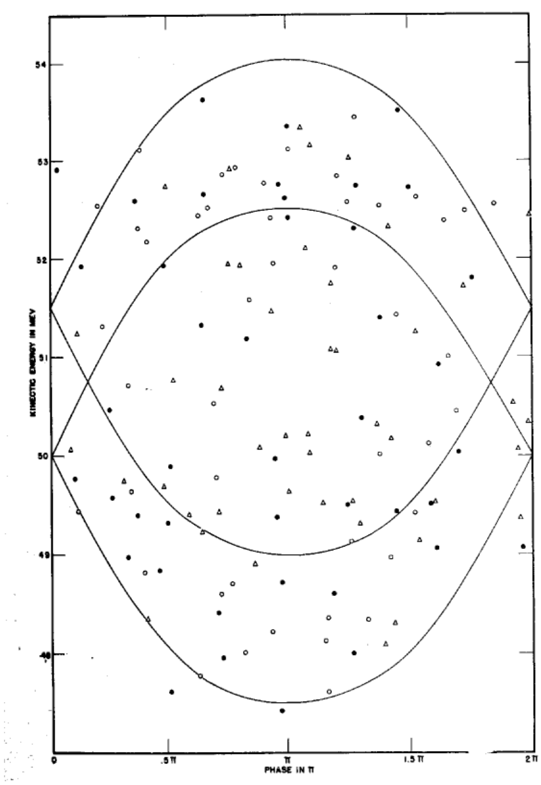

Figure 8: Scattered orbits in two overlapping buckets

COLLIDING BEAMS

The center-of-mass energy for a collision of a particle of relativistic energy E with a stationary particle is proportional to $E^{1/2}$. This suggests the energy advantage in letting two equal energy particles collide, in which case the center-of-mass energy is the sum of the energies of the colliding particles. For example, two 15 GeV protons colliding head-on produce a center-of-mass energy of 30 GeV. A single proton hitting a stationary proton would have to have an energy of 450 GeV to produce the same center-of-mass energy.

Unfortunately the cross sections are such that the event rate for accelerator beams achievable up to that time would be impractically low. It was Kerst who observed that with the intensity achievable with stacked beams, colliding beam experiments become practical.[2]

I remember being invited to give a colloquium on this subject at the University of Illinois. When I mentioned colliding beams, the audience burst out laughing. I was somewhat taken aback until I learned later that the week before professors Kerst and Kruger had shot pea shooters at each other from opposite sides of the stage.

50 MEV MODEL

A 50 MeV electron model was constructed which first operated in 1961. (See Figure 9.) It was a radial sector machine with two identical magnets in each sector, with oppositely directed magnetic fields. It was first pointed out by Ohkawa that particles in such a machine can circulate in either direction, and that the orbits are closed because they are at larger radii in the positive magnets. This configuration would allow colliding beams in a single machine. However the ratio of circumference to that for a uniform field is about 8.

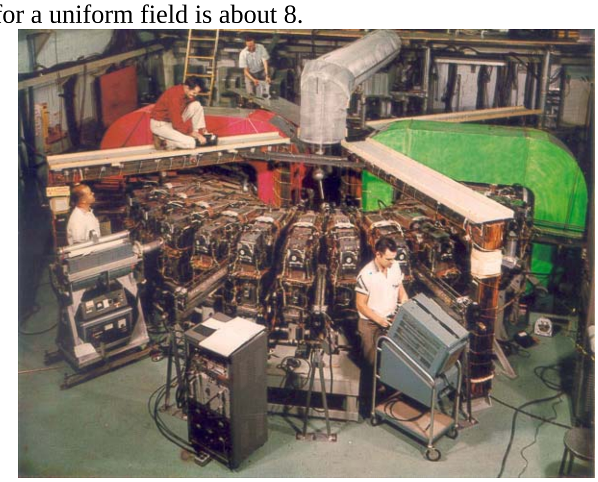

Figure 9: 50 MeV Model

The machine was successfully operated in the two-way mode. However most of the experiments were performed in a one-way mode with one of each pair of magnets excited to a higher field than the other. In case we had trouble crossing the transition energy at 1.13 MeV, betatron cores were installed; they can be seen in the figure. However we were able to accelerate over the transition energy with the rf cavity, so most experiments were carried out using rf buckets from the injection energy (100 keV). The green cavity on the right powers the rf accelerating gap. We had to make up for radiation loss of a few volts per turn in the stacked beam. Due to its energy spread, we would have had to use a high voltage on an accelerating gap in order to trap the stacked beam in a bucket. We therefore chose to make up the radiation loss by phase displacement, using a low voltage supplied by the red cavity on the left. Its frequency was modulated so as to move an empty bucket down through the stacked beam from above.

After compensating for positive ions with clearing electrodes, and compensating for instabilities with feedback, and providing compensation for the effect of the stacked beam current on the magnets, we succeeded in stacking a beam of over 10 amperes!

OTHER MURA CONTRIBUTIONS

FFAG Cyclotrons

Conventional cyclotrons cannot accelerate protons much above 20 to 30MeV because of the decrease in revolution frequency caused by relativistic effects and by the field gradient required for vertical focusing. Using an FFAG field, one can let the magnetic field increase with energy at such a rate as to keep the revolution frequency constant up to a much higher energy. Many FFAG cyclotrons with spiral sector geometry have been constructed. Except for their use in accelerator experiments, this is the only practical application of the FFAG accelerators.

Instabilities

The MURA working group made analytical, numerical, and experimental studies of space charge limits and collective instabilities. Carl Nielson called our attention to the negative mass instability. A detailed theoretical analysis was given in a paper at the 1959 CERN Symposium.[3]

THE END

Proposals

During its thirteen year life, MURA submitted some half-dozen proposals to the AEC for FFAG accelerators in the 10 to 20 GeV range. Some emphasized colliding beams and high intensity single beams, and some proposed only high intensity single beams. None of these proposals was approved.

Why did MURA fail?

The end of high energy FFAG accelerators was a result of two developments, in both of which MURA played a role. The first was the invention of the storage ring by Lichtenberg, Newton, and Ross[4] at MURA and independently by G.K. O'Neill[5] at Princeton and SLAC. Using many of the techniques proposed by MURA, storage rings were a much cheaper way of achieving colliding beams.

The second development was he invention of the cascade synchrotron. In 1959 MURA conducted a summer workshop to which accelerator and high energy scientists were invited to study the design and utilization of FFAG accelerators. Mathew Sands, an invitee, chose instead to study the possibility of using a rapid cycling synchrotron to inject at an intermediate energy into a second synchrotron for further acceleration. He was able to show that this scheme could achieve high beam intensities not much less than those promised by FFAG, and at much lower cost.

FFAG accelerators would have worked as proposed, but that was not the way to build high energy machines.

After MURA

In 1967 MURA disbanded and sold its site and laboratory to the University of Wisconsin-Madison. The lab became the Physical Sciences Laboratory. Ednor Rowe built a small storage ring, Tantalus, initially for orbit studies, but later converted into a synchrotron radiation source, the first dedicated synchrotron radiation source. Tantalus began the Synchrotron Radiation Center. An 800 MeV storage ring, Aladdin was later added; it is still serving many users from around the country and the world.

Some MURA people remained at PSL and SRC, and some went to Fermilab, Berkeley and Brookhaven. The location of Fermilab in the Midwest is in part due to the activities of MURA.

Conclusion

Perhaps it is a good idea, if we want to maximize progress, not to give people what they propose.

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[4]D.B. Lichtenberg, R.G. Newton and M.H. Ross, "Intersecting Beam Accelerator with Storage Ring," MURA Report 110, April 26, 1956.

[5] G.K. O'Neill, Phys. Rev., **102**, 1418, 1956.

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