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RLK-ASPUN(9-30-88)

THE ASPUN PROJECT*

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I. Introduction

A study of pulsed spallation neutron source,(1) that could deliver fluxes in excess of 1×10^{17} N/cm^2-sec began at Argonne in 1981. A review of various accelerator concepts to act as an intense charged particle source to generate spallation neutrons resulted in the selection of a Fixed-Field Alternating-Gradient(2) (FFAG) accelerator as the preferred device.

There are several features of an FFAG accelerator that make it well suited to be the charged particle accelerator for a 10^{17} N/cm^2-sec pulsed source. Since the main magnets are dc operated, injection time can be long enough to provide for efficient injection and adiabatic capture, the rf system can be optimized for maximum use of the accelerating voltage, the repetition rate can reach hundreds of hertz because there are no $\frac{dB}{dt}$ effects in the magnets or vacuum chamber, and large transverse and momentum acceptances are possible. The large momentum acceptance and rapid acceleration helps avoid some of the instability problems.

The conceptual design has evolved from a spiral-type FFAG with strong edge focussing(3) to a radial-type FFAG.(4) The radial-type FFAG allows easier installation of the rf cavities at the expense of higher magnetic fields. Since the magnets are dc operated, the higher field can be achieved with superconducting coils.

Repetition rates of 200 to 300 Hz are possible and reasonable with an FFAG accelerator, however, the scientific users would prefer a repetition

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rate less than 100 Hz. The earliest FFAG designs considered internal stacking in energy space of several injected pulses at an energy near the extraction energy and then final acceleration of the stacked pulses to full energy and extraction as a single pulse. This technique was successfully demonstrated on the early MURA-FFAG accelerators.(2) However, some problems are encountered when applying this technique to a spallation source driver in which the goal for efficiency of extracted beam to injected beam is 99.9% or better. In order to stack at an intermediate energy, the energy spread of the injected beam is limited to be able to stack several bunches into the acceptance of the rf bucket. This potentially could reduce the threshold for the microwave instability at injection to where beam losses could occur. Also, the stacking technique requires adiabatically debunching, merging, and rebunching, with virtually no losses, several injected bunches that are accelerated to the stacking energy before final acceleration and extraction of the single stacked bunch. A technically less demanding concept using one or two external pulse accumulation rings is presently proposed.

II. Fixed-Field Alternating-Gradient Accelerator Design

The guide field in an FFAG accelerator as a function of radius is given by

$$B = B_o(R/R_o)^k$$

where R is the average radius given by the integrated path length of the accelerated particle divided by 2π, and B_o is the magnetic field at a reference radius R_o. Each lattice cell consists of horizontally-focussing and defocussing magnets, the latter being of weaker field. Meads and Wüstefeld suggest a DFD combination(4) in which the horizontally positive and negative bending fields occupy equal lengths along the circumference, but the field of negative bending section is half the field in the positive bending section and divided in two equal lengths before and after the positive bending section. The magnetic field profile along the particle path is shown in Fig. 1.

Figure 2 shows the plan view of a 1500-MeV radial-FFAG accelerator presented by Meads and Wüstefeld at the 1985 Particle Accelerator Conference.(4) There are 20 identical bending magnet sectors which occupy about 35% of the circumference of the ring. The value of the field index, k, is 13.4. The parameters for an FFAG accelerator for ASPUN are given in Table 1. The transverse β-functions for a half-sector are shown in Fig. 3. Deviations of the actual radial position from the mean orbit described by a circle with radius, R, are shown in Fig. 4 as a function of position along the orbit.

Since the magnetic fields of an FFAG accelerator are highly nonlinear, it is necessary to ensure that the beam emittances are well within the stability limits defined by the nonlinear terms. A computer program written by Meads(5) was used to calculate the limits in the vertical and horizontal planes. The 500-πmmmr vertical emittance and 650-πmmmr horizontal emittance are shown in relation to the calculated stability limits in Figs. 5 and 6, respectively.

H^- beam is injected from a linac on the inside radius of the accelerator. Four bumper magnets are used to locally deflect the closed orbit onto a stripper foil for stripping the H^- to H^+. The fields of the bumper magnets are reduced during injection so the beam is more uniformly distributed over phase space. Approximately 38.5 mA of H^- beam is injected over a 500-μs period in order to reach 1.2×10^{14} protons.

The proposed injection energy is 350 MeV. The incoherent space charge limit for number of injected particles, N, is given by

$$N = \frac{\pi[\varepsilon_z + \sqrt{(\nu_z \varepsilon_x \varepsilon_z)/\nu_x}\;]\beta^2 \gamma^3 \Delta\nu_z B_f}{r_p\ F}$$

where ε_x and ε_z are the horizontal and vertical emittances, β is the relativistic velocity of the injected particle, γ is the relativistic mass of the injected particle $\Delta\nu_z$ is the allowable tune shift, B_f is the circumferential bunching factor, r_p is 1.54×10^{-18} m, and F is the transverse bunching factor.

It is planned to program the rf during capture and initial acceleration to keep B_f at 0.375 or larger. It is assumed that the horizontal beam distribution can be made reasonably uniform and that the distribution in vertical space will be nearly quadratic. These conditions lead to a value of F equal to 1.35. If the allowable tune shift is 0.25, the space charge limit should be about 1.72×10^{14} protons per pulse. The proposed operating level is about 70% of the calculated space-charge limit.

Acceleration to full energy of 1500 MeV is accomplished in about 2.5 ms requiring an average accelerating voltage of about 260 kV. The design is for a maximum voltage of 400 kV to operate at a stable phase angle of 40°. The first 250 μs after injection are used for adiabatic capture of the beam during which time the rf voltage increases to about 150 kV. Operation at full voltage does not start immediately after the capture period to avoid bunching the beam too rapidly. The rf voltage increases from 150 kV to the full 400 kV in about 700 μs. The whole cycle from start of injection to extraction takes 4 ms. During the 500-μs injection period, the cavity is retuned to the injection frequency, 1.241 MHz.

The average accelerating voltage per length of straight section is 10 kV/m for ferrite-loaded cavities. Ten straight sections are used for 20 rf cavities developing 20 kV each. The beam loading is fairly large with roughly 20% to 30% of the total stored energy delivered in each passage of the beam. However, a number of techniques have been suggested for handling beam loading at this level.(6-8)

Extraction of the beam is performed in one turn using ferrite kicker magnets located on the outside radius of the accelerator. The extracted beam pulse should be about 160 to 200-ns long. Allowing for some dilution in transverse space that might occur during acceleration, the design values for emittances in transverse space are $\varepsilon_x = 410$ πmmmr and $\varepsilon_y = 315$ πmmmr at 1500 MeV.

III. Pulse Accumulation to Lower Repetition Rate on Target

The repetition rate on the target is reduced and the charge per pulse increased with the use of two external pulse accumulation rings. No design work has been done on these rings, however, a conceptual design for an isochronous compressor ring for proton beams (IKOR) was done for the SNQ project in 1981(9) and can be considered as a proof-of-principle to achieve what is necessary for the ASPUN rings.

The radius of the IKOR ring is 32.2 m. This is compatible with the FFAG for ASPUN which extends to 28.14 m plus another meter or so for the return yoke. IKOR was designed for H^- to H^+ injection and a smaller emittance, whereas for ASPUN, the injection would be with two consecutive 150 to 200-ns-long pulses. There would be two pulses with about 90-ns spacing in the ring. The fast injection kickers must have a 10% to 90% rise and fall time of about 75 to 80 ns and a 200 ns flattop. The extraction kicker magnet needs a 75-80 nanosecond risetime and 500 to 600 ns flattop. These requirements are within the present technology for ferrite-type kicker magnets.

The IKOR ring was designed to store 2.7×10^{14} protons at 1100 MeV. Similar rings for ASPUN would only need to store 2.4×10^{14} protons at 1100 MeV. The ASPUN rings would have to be isochronous at 1500 MeV and would require larger magnet apertures, but there is no reason this couldn't be done.

Four out of every five ASPUN pulses would be stored in the accumulator rings. The fifth pulse would be directed to the ASPUN target followed sequentially by the pulses stored in the accumulating rings. This would mean a train of five pulses arrive on target over about a 1.5-μs period. This pulse length is acceptable with regard to moderation times for epithermal neutrons.

IV. Conclusion

While the conceptual design for an accelerating system presented here is, in principle, able to deliver the required charge per pulse, many features still need to be developed. The whole question of controlled losses to 10^{-3} or 10^{-4} per pulse needs to be explored in depth. The goal is to be able to do hands-on maintenance on most of the accelerator components and to greatly limit the number of components that will get activated to a degree that more elaborate handling schemes are needed.

No target design has been undertaken at Argonne. The DIANNE target of SNQ(10) was taken as a proof-of-principle, but that development effort has been stopped. A major development effort is needed on the targets and modulators.

No engineering design has been undertaken for the individual accelerator components. There are no components for which the requirement exceeds the limits of the present state-of-art. However, the demands on these components are challenging and require careful design and considerable prototyping to ensure satisfactory performance.

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Table 1
Parameters for the FFAG Accelerator

Extraction Energy, Mev	1500
Extraction Radius, $\int ds/2\pi$, m	28.14 m
Injection Energy, MeV	350
Injection Radius, $\int ds/2\pi$, m	26.37
Field Index, k	13.4
Peak Positive Bending Field @ Extraction, T	4.1
Peak Negative Bending Field @ Extraction, T	1.9
Peak Positive Bending Field @ Injection, T	1.717
Peak Negative Bending Field @ Injection, T	0.796
Horizontal Tune	4.25
Vertical Tune	3.25
Horizontal Emittance, mmmr	650 π
Vertical Emittance, mmmr	500 π
Repetition Rate, Hz	250
Maximum RF Voltage, kV	400
Maximum RF Frequency (Extraction), MHz	1.565
Minimum RF Frequency (Injection), MHz	1.241

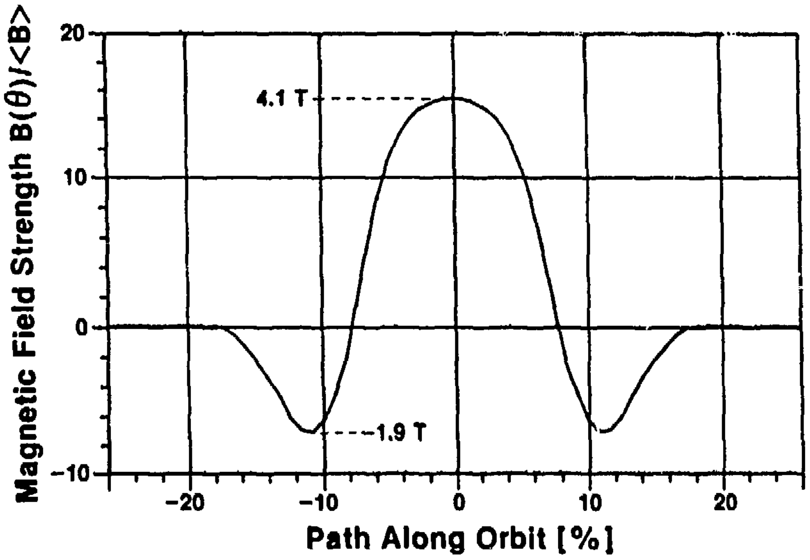

Fig. 1. Azimuthal profile of magnetic field along the path of one cell.

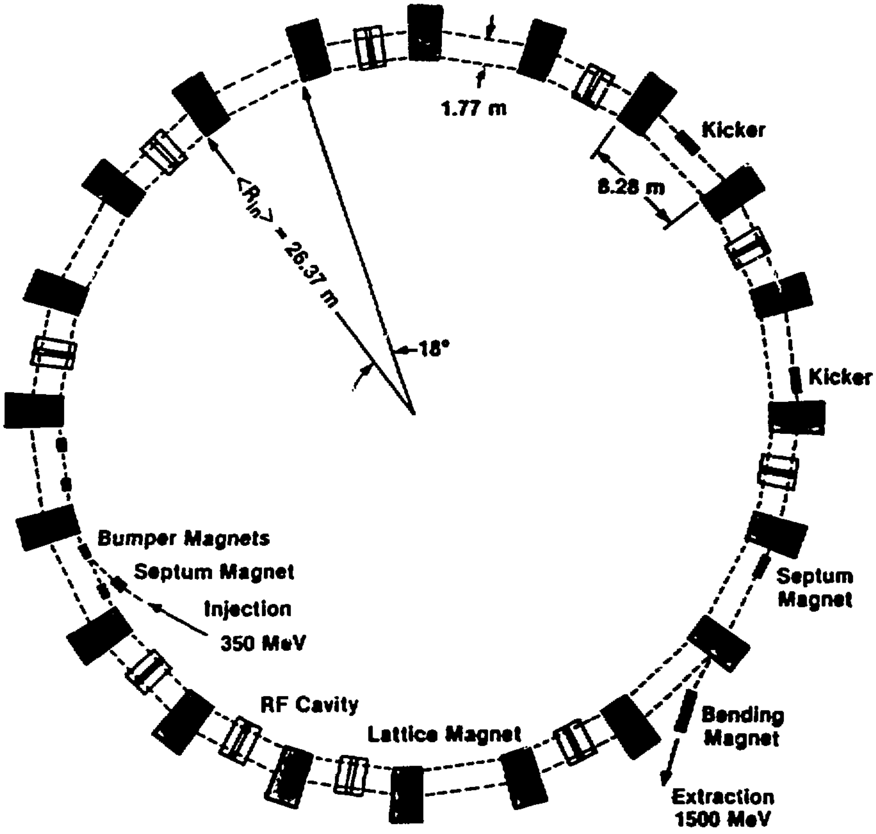

Fig. 2. Layout of radial-sector FFAG for ASPUN.

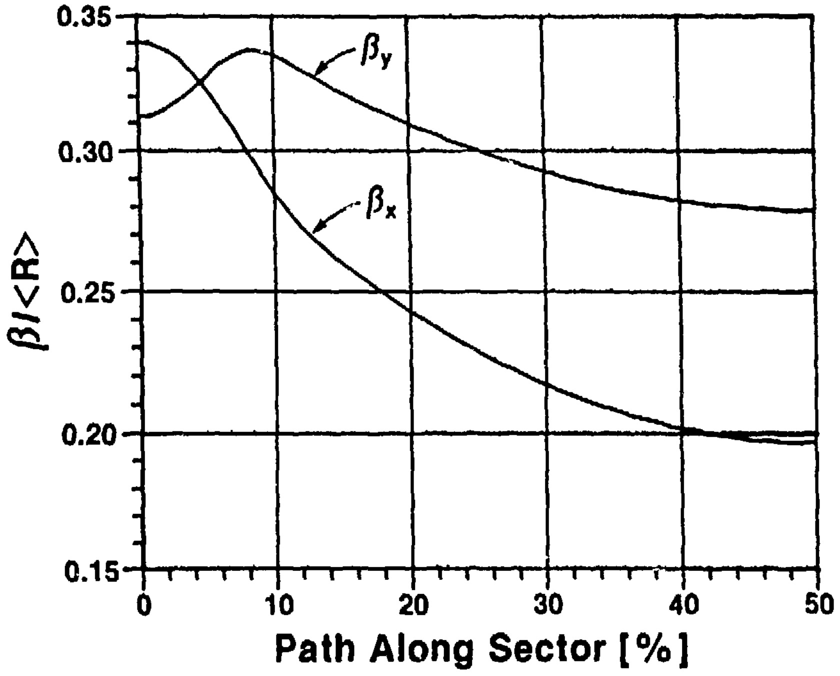

Fig. 3. Horizontal and vertical beta functions normalized to the average radius.

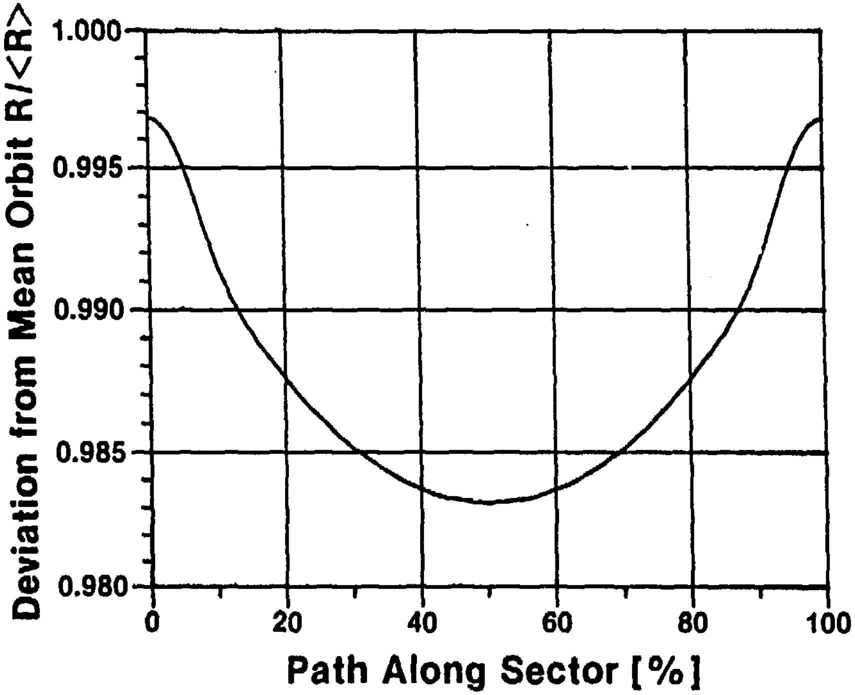

Fig. 4. Deviation of orbit from a circle of average radius, R, over a single cell length.

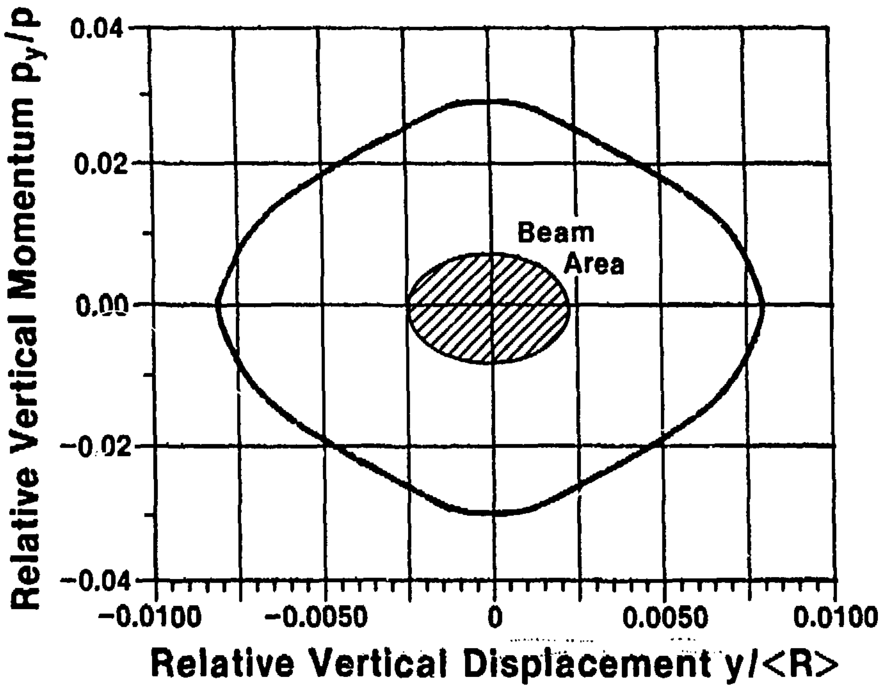

Fig. 5. Limit of beam stability in the vertical plane due to magnet nonlinearities with the 500-πmmmr emittance shown in shaded area.

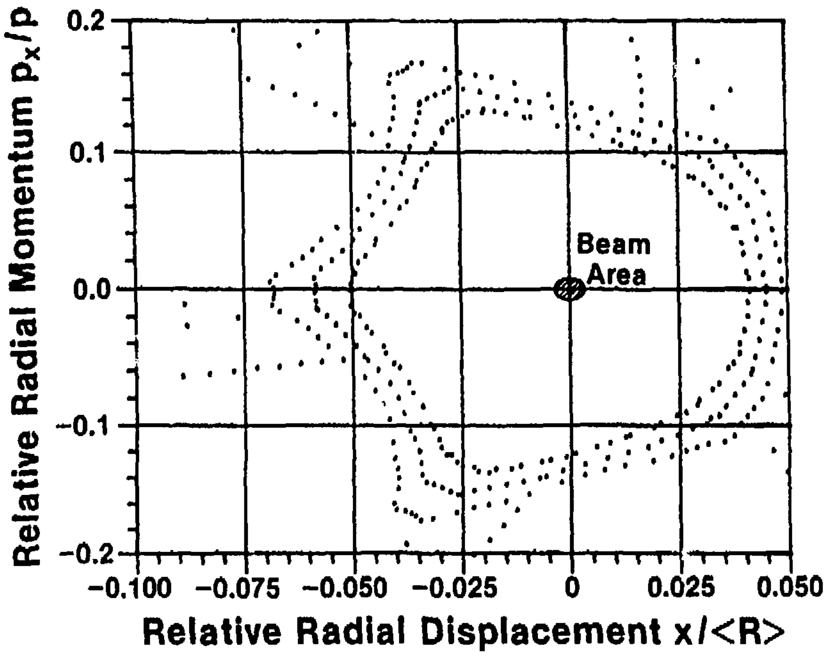

Fig. 6. Limits of beam stability in horizontal plane due to magnet nonlinearities with the 650-πmmmr beam emittance shown in shaded area.