© 1983 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.

IEEE Transactions on Nuclear Science, Vol. NS-30, No. 4, August 1983

ASPUN, DESIGN FOR AN ARGONNE SUPER INTENSE PULSED NEUTRON SOURCE*

T. K. Khoe and R. L. Kustom
Physics Division
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439

Introduction

Argonne pioneered the pulsed spallation neutron source with the ZING-P and IPNS-I concepts.[1] IPNS-I is now a reliable and actively used source for pulsed spallation neutrons. The accelerator is a 500 MeV, 8-9 μa, 30 Hz rapid cycling proton synchrotron.[2] Other proton spallation sources are now in operation or in construction. These include KENS-I at the National Laboratory for High Energy Physics in Japan,[3] the WNR/PSR at Los Alamos National Laboaratory in the USA,[4] and the SNS at the Rutherford Appleton Laboratory in England.[5]

Newer and bolder concepts are being developed for more intense pulsed spallation neutron sources. These include SNQ at the KFA Laboratory in Jülich, Germany,[6] ASTOR at the Swiss Institute for Nuclear Physics in Switzerland,[7] and ASPUN, the Argonne concept.

ASPUN is based on the Fixed-Field Alternating Gradient[8] concept. The design goal is to provide a time-averaged beam of 3.5 ma at 1100 MeV on a spallation target in intense bursts, 100-200 nanoseconds long, at a repetition rate of no more than 60 to 85 Hz.

Fixed-Field Alternating Gradient (FFAG) Design

The design is based on 200 MeV $H^- \rightarrow H^+$ stripping injection. The linac must provide 32 milliamperes of H^- beam for 500 μseconds at a 220 Hz repetition rate. A schematic view of the FFAG is shown in Figure 1 and the machine parameters are listed in Table 1.

The injection radius is 17.5 meters. Acceleration is accomplished with 10 rf cavities symmetrically located around the circumference. The equilibrium radius grows to 18.75 m at 1100 MeV. Injection time is 500 μseconds, capture time is 600 μseconds, and acceleration time is about 3400 μseconds. Extraction is accomplished with one turn ferrite extraction kicker magners. The pulse width will be about 140 nanoseconds.

The guide field in an FFAG accelerator is given by

$$B = B_o\left(\frac{r}{r_o}\right)^k\left[1 + \sum_{n=1}^{\infty} f_n \cos nN\left(\theta - \tan\xi \ln \frac{r}{r_o}\right)\right] \qquad (1)$$

where r is the radial distance from the center of the machine, k = (r/B) (dB/dr) is the mean field index, θ is the azumuthal angle, f_n is the harmonic component of the azimuthally varying field, N is the number of identical magnets, and ξ is the spiral angle.

The FFAG for ASPUN is designed with a relatively small spiral angle of 65° and a nearly sharp edge magnet so that the effective flutter, $(\Sigma f_n^2)^{1/2}$ is large. The betatron frequencies are independent of momentum.

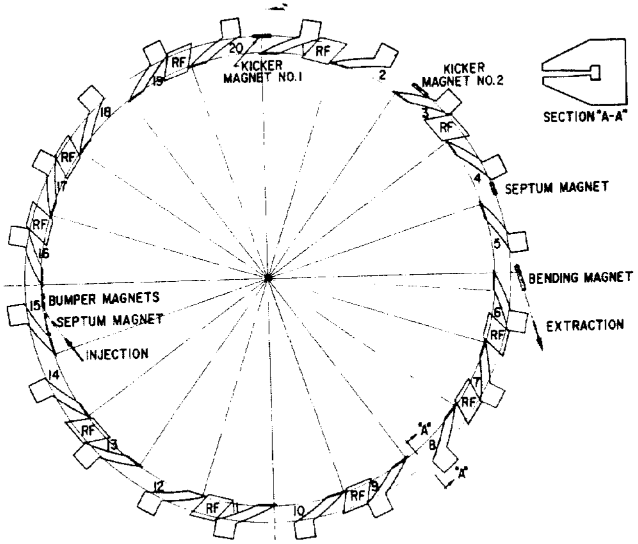

Fig. 1. Schematic View of FFAG Ring.

Table 1. FFAG Accelerator Characteristics

Injection Energy	200 MeV
Extraction Energy	1100 MeV
Injection Radius	17.5 m
Extraction Radius	18.75 m
Injection Field	0.489T
Extraction Field	1.281T
Number of Sectors	20
Angular Width of Sectors	4.5°
Field Index, k	14
Spiral Angle, ξ	65°
Radial Betatron Frequency, ν_x	4.3
Vertical Betatron Frequency, ν_z	3.25
Space Charge Limit	$>10^{14}$
Radial Beam Emittance @ 200 MeV	700π mm-mr
Vertical Beam Emittance @ 700 MeV	500π mm-mr
Frequency Range	1.544-2.259 Mhz
Maximum RF Voltage per Turn	300 kV
Harmonic Number	1
Average Current	≃3.5 ma
Repetition Rage	220 Hz
Output Energy Spread	±19.5 MeV
Output Bunch Length	136 ns

The η and β functions for this design are shown in Figure 2. They are constant with the bending radius of the equilibrium orbit within the magnet. An Enge short tail fringing field is used to calculate the focusing or defocusing effects of the magnet edges. The horizontal and vertical beam envelopes for ε_x = 700 πmm-mr and ε = 500 πmm-mr, respectively, are shown in Figure 3. The chosen values of ε_x and ε_z are sufficiently small to avoid x and z coupling and destructive vertical spread due to the nonlinear magnetic field components present in the FFAG magnet.

---

*Work supported by the U.S. Department of Energy under Contract W-31-109-Eng-38.

0018-9499/83/0800-2086$01.00© 1983 IEEE

The incoherent space charge limit of the machine is 10^{14} given by

$$N = \frac{\pi(\varepsilon_z + \sqrt{\nu_x \varepsilon x \varepsilon_z/\nu_z})\ \beta^2\gamma^3\Delta\nu_z B_f}{n_p F} \quad (2)$$

where B_f is bunching factor of 0.45 r_p is 1.54 (10^{-18}), F is the form factor of 1.5, $B_f\beta^2\gamma^3 >$ 0.375 to maintain $N > 10^{14}$. Spiral angle errors will have a large effect on the betatron frequency. The shift in tune is given by

$$\delta\nu = 2\ \frac{\sqrt{N}}{\nu}\ \frac{(\Delta\xi)\mathrm{rms}}{\sin 2\xi}. \quad (3)$$

For this design $\delta\nu$ is equal to 3.6 $(\Delta\xi)$ rms.

The good field region of the magnet must extend from 17.4 to 18.9 meters. The field at the injection radius of 17.5 meters must be 0.489T and at the extraction radius of 18.75 m must be 1.281T.

The magnet gap must allow for the betatron amplitude, field errors and misalignment, poleface windings, vacuum chamber walls, and some contingency.

To within a 98% probability, the rms displacement of the equilibrium orbit will be p times the rms displacement of an individual magnet where p is

$$p = \frac{2\pi}{|\sin\pi\nu|}\ \frac{k}{\nu\sqrt{N}}\ \sqrt{\frac{\beta_{\max}}{\beta_{\mathrm{ave}}}}\ . \quad (4)$$

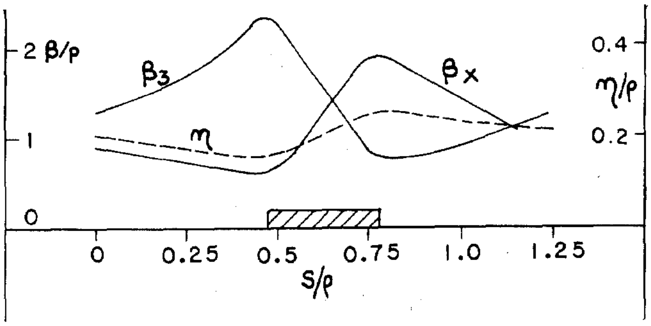

Fig. 2. η and β functions for the ASPUN FFAG.

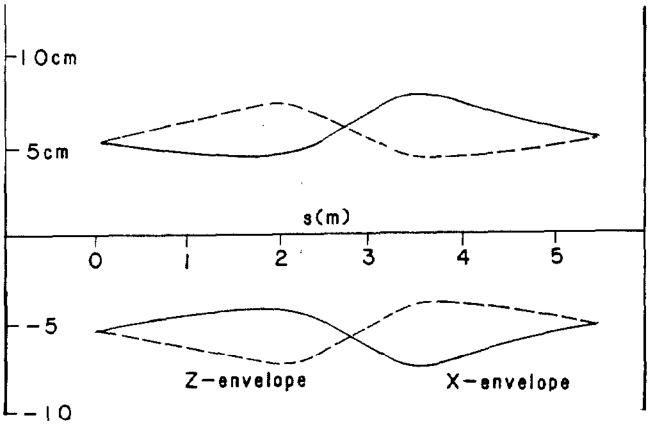

Fig. 3. Horizontal and Vertical Beam Envelopes

The tolerances for rms displacement require a 1.0 cm allowance in the gap. The total magnet gap at injection must be 20 cm which allows for 14.3 cm of betatron motion, 1.0 cm for field errors and misalignment, 1.7 cm for pole face windings, 2.0 cm for vacuum walls and 1.0 cm extra space. The gross features of magnet are shown in section A-A^1 of Figure 1. The 20 cm gap extends radially outward for 0.6 m and then tapers to 10.1 cm in another 0.9 m. Pole face windings extend over the inside 0.6 meters. The details of the magnet are given in Table 2.

The injection system is shown in Figure 4. There are 4 programed bump magnets and one programed septum magnet. The stripper foil is located between the inside two bump magnets. Initially the foil edge is located at the center of the phase plane acceptance ellipse, and then it moves away during the 500 μsecond injection period. The vertical beam is also modulated during injection so that the total density distribution is as uniform as possible.

The energy of linac beam is modulated to give a coasting beam energy spread of ±3.2 MeV. This beam is adiabatically captured in a non-accelerating rf bucket. At least 32 ma H^- beam is required for 10^{14} protons per pulse.

Acceleration is accomplished with 10 cavities each capable of a peak value of 30 kilovolts. The beam is bunched adiabatically by instantaneously applying an rf voltage of 27 kilovolts and increasing the rf voltage to 150 kV in 250 μseconds. After bunching, the rf voltage and frequency are programed to increase the energy as linearly as possible while maintaining $B_f\gamma^2\beta^3 >$ 0.375. The parameters of the accelerating system are given in Table 3. The rf voltage and frequency through out the cycle are shown in Figure 6. The kinetic energy and $\sin\phi_s$ are shown in Figure 7.

Table 2. Magnet Parameters

Minimum Pole Radius	17.4 m
Maximum Pole Radius	18.9 m
Spiral Angle	65°
Main Coil Ampere-Turns	9.7×10^4
Pole Face Widning Ampere-Turns	4.8×10^4
Weight of Yoke and Poles	68 Tons
Weight of Coils	2.5 Tons
Power Loss	140 kW

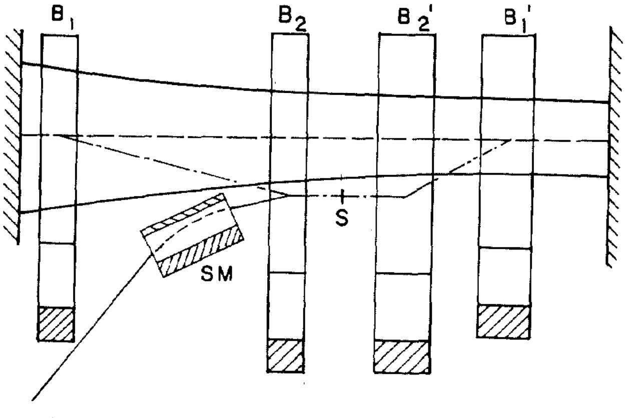

Fig. 4. Injection System Showing Four Bumper Magnets, Septum Magnet, and Stripper Foil.

Table 3. Accelerating System Parameters

Number of Cavities	10
Length of Cavity	1.9 m
Maximum Cavity Voltage	30 kV
Total Volume of Ferrite	11 m^3
Total Peak Ferrite Power Loss	1.25 MW
Cavity Shunt Impedance	7200 Ω
μ at Injection	26.8
μ at Extraction	12.5
Average rf Flux Density	0.012T
Maximum rf Flux Density	0.0145T
DC Bias at Injection	900 A/m
DC Bias at Extraction	1800 A/m

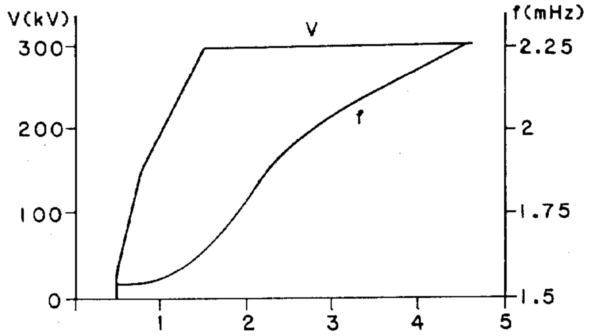

Fig. 5. RF Voltage and Frequency as a Function of Tune.

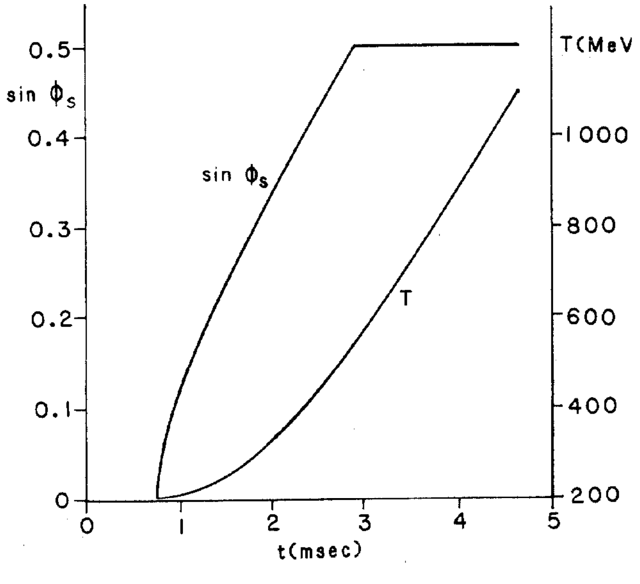

Fig. 6. Kinetic Energy and $\sin\phi_s$ as a Function of Tune.

Extraction elements are shown in Figure 1. The ferrite kickers have a peak field of 0.0625T and 1.0 meter length of ferrite. The first kicker kicks the beam inward by 10.34 mr and the second kicker kicks the beam outward by 10.34 mrad. The betatron phase advance between the two kickers is 180°. The septum magnet is one meter long, has a magnetic field of 0.376T, and bends the beam by 62.3 mrad. It is located 100° in betatron phase from the second kicker. The final bending magnet is 2 m long, has a field of 1.4T and bends the beam by 460 mrd.

Discussion

The ASPUN conceptual design is by no means a complete and final facility design. It is, however, indicative of the potential of the FFAG concept. An accelerator of this capability will have very exciting possibilities as a driver for a spallation source. The neutron fluxes from a facility built around this concept should exceed by at least an order of magnitude the fluxes that will be possible with the facilities now under construction.

The concept will be studied in considerably more detail at Argonne in the next few years. Clearly, beam losses in this machine must be less than 10^{-4} or 10^{-3}. Preliminary calculations indicate that capture, acceleration, and extraction could achieve this efficiency, but his is an area that will receive considerable attention. Also, magnet design and beam orbit programs will be pursued.

References

1. J. M. Carpenter and David L. Price, "An Intense Pulsed Neutron Source for Argonne National Laboratory," IEEE Transactions on Nuclear Science, Vol. NS-22, No. 3, June, 1975, p. 1768.

2. R. L. Kustom, "Intense Pulsed Neutron Sources," IEEE Transactions on Nuclear Science, Vol. NS-28, NO. 3, June, 1981.

3. H. Sasaki, "The Booser Synchrotron Utilization Facility at KEK," Proceedings of the ICANS-IV Meeting, KEK, Japan, October 20-24, 1980.

4. George P. Lawrence, et al., "LASL High-Current Proton Storage Ring," Proceedings of XI International Conference on High Energy Accelerators, Geneva, Switzerland, July, 1980.

5. G. H. Rees, "A Pulsed Spallation Source for Neutron Scattering Research, "IEEE Transactions on Nuclear Science, Vol. NS-24, No. 3, June, 1977.

6. J. E. Vetter, "A High Intensity Proton Linear Accelerator for the German Spallation Neutron Source (SNQ)," IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June, 1981, p. 3455.

7. W. Joho, "Astor, Concept of a Combined Acceleration and Storage Ring for Production of Intense Pulsed or Continuous Beams of Neutrinos, Pions, Muons, Kaons, and Neutrons," this conference.

8. F. T. Cole, et al., "Electron Model Fixed Field Alternating Gradient Accelerator," Rev. Sci. Instr., 28, 1957, p. 403.