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A 1500-MeV FIXED-FIELD ALTERNATING-GRADIENT SYNCHROTRON FOR A PULSED-SPALLATION NEUTRON SOURCE*

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Introduction

Argonne is developing the design for an advanced super pulsed-spallation neutron source called ASPUN that uses a fixed-field alternating-gradient accelerator as the proton source. ASPUN is intended to be the next generation in pulsed spallation neutron sources.

The spallation source concept was pioneered at ANL,[1] an effort which has led to the successfully operating Intense Pulsed Neutron Source (IPNS).[2] IPNS uses a 500-MeV rapid cycling synchrotron as the proton source. Beam is extracted at a 30-Hz rate onto a depleted uranium target in 100-nanosecond bunches to produce intense bursts of neutrons for solid state physics experiments. The IPNS accelerator routinely delivers greater than 12 μA of timed-averaged proton current on the uranium target. Newer, more powerful pulsed spallation sources are nearly ready to start operation. The Proton Storage Ring[3] at the Los Alamos National Laboratory is designed to deliver 100-μA at 800 MeV in 12-Hz bursts and the Spallation Neutron Source[4] at the Rutherford-Appleton Laboratory in England is designed to deliver 200-μA at 800 MeV in 50-Hz bursts.

The design goal for ASPUN is to deliver peak fluxes greater than 1×10^{17} thermal neutrons/cm^2-sec at the beam port with a repetition rate of somewhere between 10 and 100 Hz. Neutron fluxes greater than 10^{17}/cm^2-sec could be achieved with an average beam current of 1380 μA at 1500 MeV provided that direct IPNS scaling is possible. However, in order to provide a sizeable safety margin in startup, the design goal for ASPUN is 3800 μA so that the accelerator need not immediately achieve full current capability or the initial target and moderator combinations need not produce neutrons as efficiently as IPNS.

The first conceptual design of the FFAG for ASPUN was an 1100-MeV, 20-sector machine with an injection radius of 17.5 m and an extraction radius of 18.75 m.[5] The conceptual design currently under study has a higher extraction energy, a larger average radius, but still has 20 sectors. The current interest in higher extraction energy is stimulated by calculations that indicate that the useful neutron production per incident proton is still increasing proportionally up to 1500 MeV.[6] The larger radius also matches existing buildings at Argonne that could be made available for the facility.

Description of the 1500-MeV FFAG

A schematic view of the 1500-MeV FFAG is shown in Fig. 1, a proposed site layout is shown in Fig. 2, and a parameter list is given in Table I.

The basic conceptual design for the ASPUN FFAG assumes a 200-MeV injection energy. This energy was chosen to achieve the highest injection energy using an Alaverz linac structure with a relatively high shunt impedance. However, parameter studies with higher injection energies are still progressing and will be discussed later.

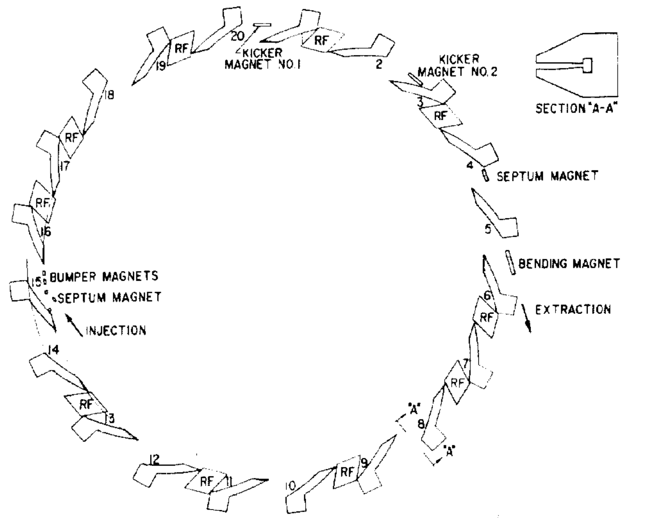

Fig. 1. Schematic View of the 1500-MeV FFAG.

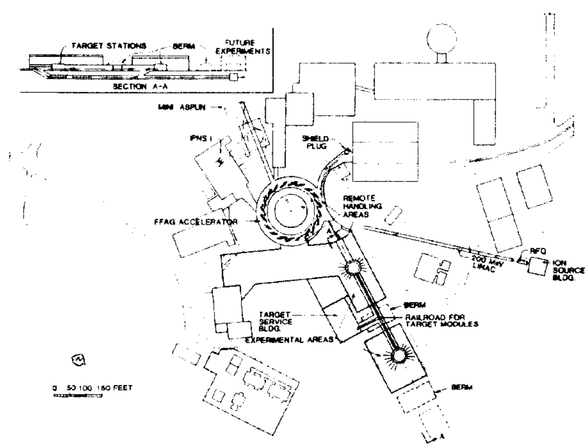

Fig. 2. Proposed site layout.

The average injection radius (circumference/2π) is 25.888 m. The average extraction radius is 28.139 m. There are 20 spiral sector magnets which provide an injection field of 0.413 T and an extraction field of 1.327 T. The spiral edge angle is 61°. The field index, $k = \left(\frac{r}{B}\frac{dB}{dr}\right)$, is 14. The magnetic field

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

where r is the radial distance from the center of the machine, θ is the azimuthal angle, f_n is the harmonic component of the azimuthally varying field, N is the number of identical magnets, and ψ is the spiral edge angle of magnets. The angular width of each spiral magnet is 3.6°. The radial and vertical tunes are 4.25 and 3.3, respectively.

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Table I
Characteristics of the Argonne Fixed-Field Alternating-Gradient Accelerator for ASPUN

Injection energy (H^-)	200 MeV
Injection radius (circumference/2 π)	25.888 m
Extraction radius (circumference/2 π)	28.139 m
Number of sector magnets	20
Magnetic field	
(injection/extraction)	0.413/1.327 T
Field index, k (R/B)(dB/dR)	14
Spiral angle	61°
Angular width of sector magnet	3.6°
Acceptance	
ε_x	650 π mm-mr
ε_y	500 π mm-mr
Betatron tune (ν_x,ν_y)	4.25/3.3
RF frequency (2nd harmonic)	2.087/3.09 MHz
(1st harmonic)	1.545/1.566 MHz
Peak RF voltage	400 kV
Number of cavities	10
Extracted beam pulse length	
- one turn	325 ns
Protons per pulse (design goal)	
(injection/extraction)	$1 \times 10^{14}/6 \times 10^{14}$
Repetition rate	45-50 Hz
Beam current (design goal)	3800 μA
Extraction energy	1500 MeV

H^- beam at 200 MeV is injected through a carton stripper foil using a four bumper magnet system and a septum. The bumper magnets are, initially, fully energized to bump the equilibrium orbit at injection into the foil for zero betatron amplitude. The bumper strength decreases over the 500 μsec period so that the injected beam fills the horizontal betatron phase space of 650 π mmmr. A pulsed vertical deflector is also planned for the injection line to similarly fill the vertical space of 500 π mmmr. The object is to achieve nearly uniform charge distribution in the transverse plane to reach the maximum space charge limit. The expectation is that by careful spacing of the charge distribution, favorable form factors and bunching factors can be achieved. The space charge limit N is given by

$$N = \frac{\left(\varepsilon_y + \sqrt{\frac{\nu_y}{\nu_x}\,\varepsilon_x\varepsilon_y}\right)\gamma^3\beta^2\,B_f\,\Delta\nu_y}{r_p F} \qquad (2)$$

where B_f is the bunching factor, F is the form factor, γ the relativistic mass, β is the relativistic velocity, ν_x and ν_y are the horizontal and vertical tunes, and r_p is 1.54 (10^{-18}). The expectation is to achieve greater than or equal to 10^{14} particles per pulse at injection by getting $F \approx 1.25$, $B_f \approx 0.55$, and $\Delta\nu_y \approx 0.25$.

RF acceleration is provided by 10 cavities, each capable of generating a peak voltage of 40 kV. The plans are to accelerate on the second harmonic from the injection energy to 1250 MeV. At this point, the acceleration is slowly stopped and the beam is left circulating. The average radius at 1250 MeV is 27.897 m. It is proposed in the reference design to stack five other injected bunches and then adiabatically recapture and accelerate 6×10^{14} particles to the extraction energy on the first harmonic. The frequency swing from injection to 1250 MeV is 2.087 to 3.090 MHz. The frequency swing for accelerating from 1250 MeV to 1500 MeV is 1.545 to 1.565 MHz.

Extraction is accomplished with a one-turn fast ferrite kicker magnet. The pulse length of the single extracted bunch is about 325 nanoseconds.

Current Studies

System Studies

Although the reference design is based on internal beam stacking at 1250 MeV, other scenarios are being considered. The use of higher injection energies and increased vertical focusing strength in the injection region is being considered so that the extracted beam goals can be achieved without internal stacking. The space charge limits with various injection energies and values $\Delta\nu_y$ = 0.25 and 0.45, using Eq. 2, are listed in Table II.

Table II
Space Charge Limit at Injection in Units of 10^{14} Protons

Injection Energy	$\Delta\nu_y = 0.25$	$\Delta\nu_y = 0.45$
200	1.29	2.32
250	1.72	3.10
300	2.18	3.92
350	2.72	4.90

Radial focusing designs based on the ideas of Mead and Wüstefeld[7] are also under consideration. With the use of the higher fields possible with superconducting coils, the relative inefficiency due to the reversed fields in a radial focussing machine are tolerable from facility and economic considerations. A parameter list of a radial machine with the same injection and extraction energy and radius is given in Table III.

Table III
Parameters for a 1500-MeV Radio Focusing Fixed-Field Alternating-Gradient Accelerator

Injection positive field	1.142 T
Injection negative field	0.410 T
Extraction positive field	3.68 T
Extraction negative field	1.32 T
Number of sectors N	20
Field index k	14.5
Radial betatron frequency	4.25
Vertical betatron frequency	3.3
Effective width of positive field	2.04°
Effective width of negative field	2 × 1.02°

Beam Loading of the RF Cavities

Typical circuit parameters for an rf cavity for ASPUN are 5.96 mH for the inductance, 1780 pfs for gap and loading capacitance, and 1.04 ohms for the series resistive losses of the tank circuit. A computer program using a fourth order Runge-Kutta technique for two variables was developed to calculate the beam loading effect.[8]

Some of the results, when 6×10^{14} protons are circulating in ASPUN, are shown in Figs. 3(a) and 3(b). Figure 3(a) shows gap voltage waveforms for full loading and no loading with an amplifier output

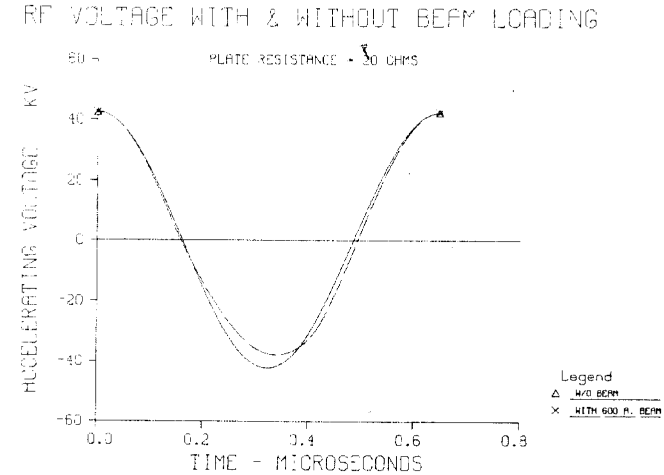

Fig. 3(a). Gap voltage waveforms with full loading and no loading with an amplifier impedance of 20 ohms.

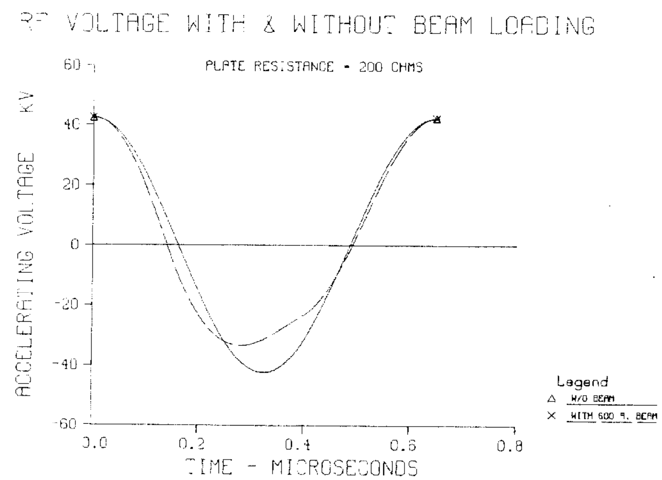

Fig. 3(b). Gap voltage waveforms with full loading and no loading with an amplifier impedance of 200 ohms.

impedance of 20 ohms. Figure 3(b) shows gap voltage waveforms for full loading and no loading with an amplifier output impedance of 200 ohms. A circulating beam of 6×10^{14} protons roughly corresponds to a peak current of 600 A in the rf bucket. Clearly, the distortion of voltage waveform shown in Fig. 3(b) for a 600-A peak is too severe to be tolerated. However, the voltage waveforms with amplifier output impedance of 10 to 20 ohms is tolerable. W. Wilhelm of the Technical University of Munich has a conceptual design for a cathode follower that can achieve the low impedances needed.[9]

Calculations show that the second harmonic voltage produces the dominant waveform distortion. Also, the size of the output resistance of the amplifier has little effect once values of about 50 to 100 ohms are reached. This suggests that an alternate solution to a cathode follower would be to use a feedback amplifier tuned to operate at and null the second harmonic voltage on the gap.

Beam Dynamics

Stability and growth times of various instabilities are under study.[10] Calculations indicate that many of the transverse instabilities have growth times that are much, much longer than the acceleration times. However, it is absolutely necessary to have a smooth wall vacuum chamber with low impedance contributions due to bumper magnets, diagnostic equipment etc. This is an area that needs to be studied in much more detail. However, all metal chambers can be used in an FFAG, since the magnets are dc excited. Also, the ferrite kicker extraction magnets are located only in the outer portion of chamber and through most of the acceleration cycle are shielded from the circulating beam. Computer programs to study orbit dynamics and the limits of beam stability in typical three-dimensional magnetic fields are also under study.[11]

Discussion

The design goals for the ASPUN FFAG are ambitious but there are reasons to believe that these goals are achievable. The problems of greatest concern are under study and technical solutions are evolving.

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