STUDY OF AN FFAG SYNCHROCYCLOTRON FOR A PULSED NEUTRON SOURCE

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ABSTRACT

A series of workshops has been held during the last year discussing the accelerator technical background for a new European pulsed spallation neutron source (ESS).[1] The basic design parameters are discussed for a high power (5MW), high current (1.7mA) FFAG synchrotron as a possible solution for the accelerator.

1. INTRODUCTION

The specification for the source was based on the requirements for future use of neutrons in condensed matter research. An average beam power of 5 MW is chosen to give an average thermalized flux of about 10^{15} n/cm^2/s, equivalent to the High Flux Reactor at ILL Grenoble. The required pulse length is less than 3 µs at a repetition rate of 50 Hz. The operation of such a source will require the highest standards in terms of availability (greater than 90%). Five different schemes have been considered as possible accelerator systems that might meet the source requirements:

1) A linear induction accelerator.
2) A linac followed by collector rings and rapid and medium cycling synchrotrons accelerating a relatively low current (125 µA) to a rather high energy (40 GeV).
3) A linac followed by a rapid cycling synchrotron.
4) A linac followed by a number of compressor rings.
5) A linac followed by a Fixed Field Alternating Gradient (FFAG) synchrotron.

Here the FFAG alternative is discussed in terms of its basic design parameters as well as a more general listing of its advantages and disadvantages. Preliminary calculations of the magnets demonstrate the feasibility of such complex magnets.

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2. GENERAL FEATURES OF FFAG TYPE ACCELERATORS

We first list the advantages and disadvantages of an FFAG for a 5 MW beam power, 50 Hz repetition rate facility with less than 3 µs pulse length.

2.1 Advantages:

About 80% of the total beam power is gained in the FFAG ring. This makes the power of the injector linac rather low, and the neutron flux associated with injection losses also relatively low.

The time structure of the injector linac is relaxed, because the adiabatic trapping makes the chopping of the linac beam unnecessary. The chopper system, which is required for the compressor ring solution, provides a time structure in the linac beam to minimize the losses associated with the injection into the compressor rings. It provides a zero-intensity interval of about 100 ns every microsecond; this means a substantial fraction of the beam will be delivered during transient portions of the rf field.

A higher energy means a lower number of particles for the equivalent power. This results in smaller transverse apertures and smaller peak current per pulse, or shorter pulses.

The losses for charge exchange injection are less critical the lower the beam power and energy at injection into the ring is. These losses are mainly caused during the trapping right after injection.

The larger the energy gain in the FFAG the lower are the losses during the trapping procedure.

The beam losses during the acceleration process are very small relative to the rapid-cycling synchrotron option because:

—The main field is dc (no pulsed magnets).
—The radial aperture is large.
—The momentum acceptance is very large.
—The shimming of dc magnets is easy.

Good stability conditions: the beam does not see the ferrites of the extraction kickers except for the last few turns, therefore coherent instabilities are relaxed.

The stacking of beam at an energy between injection and extraction is a future option for intensity upgrading.

A higher repetition frequency can easily be realized at a later stage.

2.2 Disadvantages:

The FFAG is not an existing machine. The evaluation of reliability and performance needs special discussion.

The magnets are very large, with a high flux up to 4 Tesla. The radial type magnets are not complicated, but so far no prototypes have been studied.

The working point is determined by the hardware of the magnets. Special systems (e.g., pole-face windings) need to be built for the fine tuning.

The operation of superconductors in the radiation field requires special attention to the losses.

Ferrite-tuned cavities require large ceramic windows for the acceleration gap.

Concepts for non ferrite loaded RF systems such as rotating capacitors (ROTCO) need additional study.

The high beam intensity requires special studies of beam loading effects.

The shielding for higher energy is more costly.

The operational costs for the FFAG cannot be based on existing operating machines.

3. BASIC DESIGN FEATURES AND OPTIMIZATION OF THE BASIC PARAMETERS

In the range of 1-3 GeV, the required proton beam power for a given thermal neutron flux is approximately independent of the incident proton energy. The repetition rate of 50 Hz is specified by the user community. The rf harmonic is the first or second in order to avoid coupled bunch instabilities.

If we assume $2 \cdot 10^{14}$ accelerated ions—a figure achieved at the CERN ISR—the final energy must be 3.12 GeV; a 50% increase in the number of accelerated ions would reduce the maximum energy to 2 GeV. The higher energy means higher bending magnet strength, but it does provide a number of advantages. For comparable Laslett tune shifts, the injection energy for $2 \cdot 10^{14}$ would be 430 MeV, whereas that for $3 \cdot 10^{14}$ would be 560 MeV. Choosing the lower intensity means a power gain in the FFAG of a factor of 7 rather than 4.

From experience at both the Rutherford and Los Alamos neutron sources, the most severe particle losses are at the injection energy. This is partially due to losses in the charge-exchange injection process and partially due to incomplete longitudinal trapping into the rf bucket. Both machines are limited by activation due to these losses. We expect such losses in the FFAG to be much smaller because the dc magnetic field provides ample time for careful trapping, and the injected beam will make few traversals of the stripping foil due to the brightness of the beam and short injection time. Because the threshold for the most damaging neutron-producing events is 100 MeV, the neutron production in the FFAG due to injection losses will be only about one tenth that for comparable losses in the compressor ring option.

There should be virtually no losses after the trapping is completed because there is no changing magnetic field to track. The vacuum chamber will be very smooth over most of the accelerating range, and the extraction kicker magnet will not be seen by the beam until it reaches full energy; coherent instabilities should be much less severe than for a comparable normal synchrotron.

In a scaling FFAG, the average magnetic field increases with average radius as $\langle r \rangle^k$. Gamma transition is given by $\gamma_{tr} = \sqrt{(k+1)}$. We would like to choose ring parameters to avoid the crossing of γ_{tr} in order to avoid the possible exciting of strong longitudinal beam oscillations, possible emittance blow-up, and, in the worst case, particle losses. Because the relativistic γ at 3 GeV is 4.197, we consequently desire that the field index, k, should not be less than 20. The radial tune will be close to γ_{tr} and thus around 4-5. For the optimum phase advance of 70° or so (to insure a small and smooth beam envelope), we will need about 20 sectors. The radius should be larger than 40 m in order to provide adequate room for the rf cavities, the injection and the extraction systems. The radial magnet width is determined by the field index, k, and the injection and extraction energies. For the values, k=25, T_{inj}=500 MeV, and T_{ext}=3 GeV, the radial aperture is 2.5 m.

4. BEAM DYNAMICS CALCULATIONS

The sector model used comprises one positive magnet placed between two negative magnets to enhance the flutter and consequently the vertical focusing. The field between the two magnets is assumed to follow a COSINE curve from 0 to π with a width appropriate to the magnet gap, and the separation is arbitrary. On the outer side of the negative magnets, the field is assumed to go zero as a COS^2 function with an arbitrary width. The length of the plateau region of the negative magnets is specified, and that of the positive magnet is calculated to provide the required net bending angle. In the absence of a return yoke, the field from one coil pair would have this qualitative shape.

The ORBIT program was originally written during 1983-1985 to study FFAGs for the German SNQ program.[2] It calculates quickly, by orbit integration, the properties of a general *scaling* FFAG (where all orbits are photographic enlargements of a reference orbit). The exact equations of motion are used, and the axial field at the reference orbit, which is entirely arbitrary, is input. The code has been recently extended to treat the model currently considered by surveying the parameter space and calculating the dynamic aperture. A new option to include terms to the fifth power in the axial displacement shows that the effects of these terms on the dynamic aperture are small—typically less than 1%.

Injection will be done by charge exchange of H^- ions from a linac. For a 100 mA beam, the current requirement of the FFAG is reached in 0.32 msec or about 262 turns. The linac beam is already so bright that we do not wish to place more than one turn in a given volume of phase space, and thus we will arrange the injection such that most ions will pass through the stripping foil only one time.

Extraction will be done in a single turn with a fast kicker. The kicker impedance is seen by the beam near full energy only at the end of the acceleration cycle.

5. MAGNET DESIGN

Vertical focusing in a radial FFAG is due primarily to the alternating gradient created by the presence of negative gradient magnets; that in a spiral FFAG is due to the edge angles as is the case in a typical isochronous cyclotron. Because of orbit scalloping there is some edge angle focusing in a pure radial machine. In the absence of negative field magnets, there must be strong spiral angles (60-70°), and such large spiral angles induce significant nonlinearities. Although these nonlinearities are beneficial in expanding the tune spread to provide Landau damping, they do significantly reduce the single particle stability limits. As was already shown in 1985, a pure radial machine becomes reasonably compact if strong magnetic fields of 4 T are used.[3] Thus we here seek a compromise of a machine with a modest spiral angle (~30°), a feasible positive field (~4T), and an easily obtained negative "gully" field (~ -2T).

The basic design for a radial type FFAG magnet has been studied[4] using the 3-D program PROFI.[5] The detailed design is of a magnet with a main pole 1.0 m (azimuthal) by 3.2 m (radial) and two poles carrying the return field. The field varies in radial direction between 1.16 and 3.5 Tesla, corresponding to a field index of k=15; the ratio of positive to negative bending is 3.02. The azimuthal field distribution through one half of the magnet

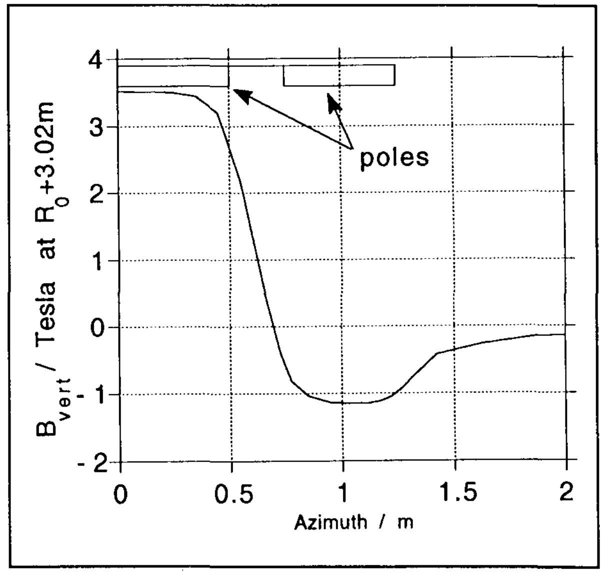

Figure 1. FFAG—Midplane Field at Extraction

is shown in Figure 1. The remaining flux, which is not used for the gully fields, is guided back through a return yoke. Additional calculations demonstrate the possibility of going up with the maximum field to 4.4 Tesla, of realizing a field index of k=26, and of adjusting the ratio of peak to gully field between 2 and 5. More detailed design studies will be done after the optical parameters of the FFAG are fixed.

6. RF STUDIES

The main characteristics of the accelerating system in an FFAG are the existence of a large accelerating gap in the radial direction (2.5 m)—as in a cyclotron—and, at the same time, the need to modulate the resonant frequency—as in synchrotrons. The first, together with a relatively low frequency (less than 2 MHz), implies large geometric dimensions of the cavity. If we accept the standard method of changing frequencies employed in conventional synchrotrons, then ferrites would be used to increase the cavity frequency. In this case, the large cavity volume will require a large ferrite volume resulting in a high price. Such a structure was suggested for the MINI ASPUN project of ANL.[6] An accelerating system for ESS, based on this report, was presented during EPAC-1992.[7] This cavity is a rectangular box extending a quarter wave along the beam path with specially shaped accelerating electrodes in the radial beam plane. The variation of the resonant frequency is accomplished through a polarization current wrapped around the ferrites. Ceramic insulators may be used in the accelerating gap to separate the vacuum volume from that containing the ferrites. However, the creation of the 2m long insulator to hold high vacuum with high reliability is expected to be a very complicated design problem.

The main parameters of this structure are contained in Table I.

Table I Properties of the FFAG rf system.

frequency range	1.66-2.06	Mhz
harmonic number	2	
accelerating Voltage/ turn	200	keV
cavity voltage	20	kV
number of cavities	10	
$B_{ferrite}$	0.0150	Tesla
ferrite volume/cavity	2.4	m^3
ferrite μ	64.9-100	
shunt impedance	8800	Ohm
maximum current	230	A
stored power	0.22	MVA
power losses/cavity	23	kW
peak power density lost	94	(kW/m^3)

The possibility of varying the resonant frequency by means of a rotating capacitor may be taken into account as well. In this case, there should be a special design to reduce the resonant line down to 3-5 m length. The weakest component and most complicated design task of such a structure would be the rotating condenser (ROTCO). Taking into account that the highest voltage achieved on the ROTCO plates is 40 kV[8)], one would need at least five such accelerating cavities. One advantage of this scheme is the reduction in power (less than 100 kW required). This compares favorably with the ferrite loaded cavities, where substantially more power is required. We will also consider a hybrid system containing both a rotating condenser and biased ferrites to provide tuning variability.

The frequency can be reset very quickly so that capture and acceleration of a new bunch can start virtually immediately after the extraction of the previous bunch. After capture and bunching, the maximum voltage is applied for the duration of the cycle in contrast to the sinusoid used in a conventional synchrotron. These considerations yield a substantially reduced cavity voltage for a given repetition rate as compared to a normal synchrotron.

If a faster acceleration time should turn out to be advisable to limit the time over which instabilities act, more rf power can be added. With such an increase, the repetition rate could be increased to obtain a greater current throughput.

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